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WASP - A FLEXIBLE FORTRAN IV COMPUTER CODE FOR CALCULATING WATER AND STEAM PROPERTIES

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SUMMARY

A FORTRAN IV subprogram, WASP, was developed to calculate the thermodynamic and transport properties of water and steam. The temperature range is from the triple point to 1750 K, and the pressure range is from 0.1 to 100 MN/m^2 (1 to 1000 bars) for the thermodynamic properties and to 50 MN/m^2 (500 bars) for thermal conductivity and to 80 MN/m^2 (800 bars) for viscosity. WASP accepts any two of pressure, temperature, and density as input conditions. In addition, pressure and either entropy or enthalpy are also allowable input variables. This flexibility is especially useful in cycle analysis. The properties available in any combination as output include temperature, density, pressure, entropy, enthalpy, specific heats (C_p and C_v), sonic velocity, $(\partial P/\partial \rho)_T$, $(\partial P/\partial T)_\rho$, viscosity, thermal conductivity, surface tension, and the Laplace constant.

The subroutine structure is modular so that the user can choose only those subroutines necessary to his calculations. Metastable calculations can also be made by using WASP.

INTRODUCTION

Water is inert, inexpensive, and available. It is used for cooling equipment, for heating or cooling other fluids, as a modeling fluid, and in many cases as the primary test fluid in heat-transfer and fluid dynamics research.

Printed tables of water and steam properties have been available to the engineer for many years, the latest accepted editions being references 1 and 2. Numerous computer codes to interpolate these tables using a variety of curve-fit and interpolation techniques are available. Many are cumbersome or lack the ability to calculate a consistent set of properties for a given point in the fluid surface. Some are designed for specific uses and do not include all the properties. A comprehensive, flexible, and internally consistent computer code for water properties was needed at the Lewis Research Center.

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16. Abstract

A FORTRAN IV subprogram, WASP, was developed to calculate the thermodynamic and transport properties of water and steam. The temperature range is from the triple point to 1750 K, and the pressure range is from 0.1 to 100 MN/m^2 (1 to 1000 bars) for the thermodynamic properties and to 50 MN/m^2 (500 bars) for thermal conductivity and to 80 MN/m^2 (800 bars) for viscosity. WASP accepts any two of pressure, temperature, and density as input conditions. In addition, pressure and either entropy or enthalpy are also allowable input variables. This flexibility is especially useful in cycle analysis. The properties available in any combination as output include temperature, density, pressure, entropy, enthalpy, specific heats (C_p and C_v), sonic velocity, $(\partial P/\partial \rho)_T$, $(\partial P/\partial T)_\rho$, viscosity, thermal conductivity, surface tension, and the Laplace constant. The subroutine structure is modular so that the user can choose only those subroutines necessary to his calculations. Metastable calculations can also be made by using WASP.

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In determining the coefficients of equation (1), the temperature data were all expressed on the thermodynamic Celsius temperature scale. Since experimental observations for water, however, are usually reported in terms of the International Practical Scale (the I. P. Scale), a lengthy discussion and a graph of the relation between the I. P. Scale and the thermodynamic temperature scale are presented in reference 3.[2]

The critical constants of reference 3 differ from those presented in references 1 and 2 as follows:

	Reference 3	References 1 and 2
Critical pressure, P_c, MN/m^2	22.089	22.120
Critical temperature, T_c, ^oC	374.02	374.15
Critical density, ρ_c, g/cm^3	0.317	0.31546

The temperatures in this table are on the I. P. Scale. The critical temperature T_c of reference 3 on the thermodynamic scale is 374.136° C.

The WASP subprogram was developed to be used in fluid-flow and heat-transfer calculations. There are independent calls for obtaining any one of the three state variables (pressure, density, and temperature) as a function of the other two (see table I, OPERATIONS SHEET FOR SUBROUTINE WASP). In addition, temperature and all the other properties can be obtained as a function of pressure and enthalpy (or pressure and entropy). This option is of considerable value in forced-convection studies and cycle analysis.

While enthalpy, entropy, and specific heats (C_p and C_v) are available in reference 3, the sonic velocity, viscosity, thermal conductivity, and surface tension were not computed in reference 3. The sonic velocity, equation (B30), is defined in terms of equation (1). The transport properties are discussed in the following section.

TRANSPORT PROPERTY CALCULATIONS

The thermal conductivity, viscosity, and surface tension are available in references

[2]Differences between the current conversion from Celsius to I. P. Scale and that of ref. 3 are small except at elevated temperatures. These deviations did not warrant our reexamination of equation (1).

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WASP is a FORTRAN IV subprogram developed for engineering calculations. The thermodynamic properties are calculated by using the Helmholtz free-energy equation developed by Keyes, Keenan, Hill, and Moore (ref. 3). The transport properties are calculated by using curve fits given in references 1 and 2 in regions where these equations exist. The authors developed their own approximations based on the tabulated values of references 1 and 2 where curve fits were not available.

The main section of this report is directed to the research-oriented user of WASP. It includes a brief discussion of the equations used in calculating thermodynamic and transport properties. Comparisons to the International Skeleton Tables and the validity of transport calculations are also discussed. A detailed presentation of user instructions is included together with a tabular summary for later reference. Detailed information about the computer program and the equations used are included as appendixes. The symbols are defined in appendix A; the property equations of WASP are given in appendix B; the important subroutines of WASP are described in appendix C; the modular design of WASP is presented in appendix D; the program listing and flow chart are presented in appendix E, the test program output in appendix F, the metastable subroutine PMETAS in appendix G, and the thermodynamic relations and derivatives in appendix H.

THERMODYNAMIC CALCULATIONS

Keyes, Keenan, Hill, and Moore (ref. 3) fit the available experimental water and steam data from the triple point to a pressure of 100 MN/m^2 and to a temperature of about 1750 K, using the fundamental equation

$$\begin{aligned}\psi &= \psi(T, \rho) \\ &= \psi_0(T) + RT\left[\ln \rho + \rho Q(\rho, \tau)\right] \qquad (1)\end{aligned}$$

where ψ is the specific Helmholtz free energy and $\tau = 1000/T$. The specific forms of $\psi_0(T)$, $Q(\rho, \tau)$, and the derivatives of $Q(\rho, \tau)$ are presented in appendix B.

Most investigators (e.g., refs. 4 to 7), in order to represent their measured values as closely as possible, have selected a modified virial equation of state

$$\begin{aligned}P &= P(T, \rho) \\ &= \sum_{i=1}^{6} A_i(T)\rho^i + \sum_{j=1}^{2} B_j(T)\rho^{2j+1}e^{-c\rho^2} \qquad (2)\end{aligned}$$

where P is the pressure and the coefficients $A_i(T)$ and $B_j(T)$ are usually polynomials in T and T^{-1}.

While the derivation of pressure from equation (1) is quite simple,

$$P = \rho^2\left(\frac{\partial\psi}{\partial\rho}\right)_T$$

$$= \rho RT\left(1 + \rho Q + \rho^2 \frac{\partial Q}{\partial\rho}\right) \tag{3}$$

the ensuing expanded descriptions for both equations (2) and (3) are quite involved, see appendix B and reference 8.

One should note the influence of the modified forms of the Benedict-Webb-Rubin (BWR) equation of state (see refs. 4 to 6) and the more recent work of Bender (ref. 7) on equation (1). (Compare the form of Q in eq. (B4) of appendix B with eq. (2).) The authors of references 5 and 6 added new exponential terms to the BWR equation of reference 4 to account for high-density effects. The technique has been successfully applied to several cryogens. More recently, Bender (ref. 7), in addition to these modifications, imposed another constraint, namely that the Maxwell Phase Rule must be satisfied; the constraint requires that the Gibbs free energy for the saturation liquid and vapor be equal. This latter constraint, although not stated explicitly, is implicitly satisfied by equation (1) (taken from ref. 3) because the Gibbs free energy of the saturated liquid and vapor are "virtually identical."

Both equations (1) and (2) have been fit by using a weighted least-squares technique which minimizes the residuals in pressure subject to various constraints such as

$$\left(\frac{\partial P}{\partial\rho}\right)_T = 0 \qquad \left(\frac{\partial^2 P}{\partial\rho^2}\right)_T = 0 \qquad \rho = \rho_c \qquad T = T_c$$

at the thermodynamic critical point. Reference 3 cites 14 such constraints; usually, the number is about one-half as many. However, the advantage of the reference 3 approach is that ψ as a function of ρ and T is a fundamental equation and all thermodynamic properties are obtained directly from ψ and its derivatives. In equation (2), P as a function of ρ and T is a state equation. In determining properties such as enthalpy, entropy, and specific heats, the state equation must be differentiated and integrated and the associated constants of integration must be determined from other data.[1]

[1]The mathematical form of the derived and integrated equations must be such that they do not possess singularities except at the critical point.

In determining the coefficients of equation (1), the temperature data were all expressed on the thermodynamic Celsius temperature scale. Since experimental observations for water, however, are usually reported in terms of the International Practical Scale (the I. P. Scale), a lengthy discussion and a graph of the relation between the I. P. Scale and the thermodynamic temperature scale are presented in reference 3.[2]

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While enthalpy, entropy, and specific heats (C_p and C_v) are available in reference 3, the sonic velocity, viscosity, thermal conductivity, and surface tension were not computed in reference 3. The sonic velocity, equation (B30), is defined in terms of equation (1). The transport properties are discussed in the following section.

TRANSPORT PROPERTY CALCULATIONS

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1 and 2, with the exception of a small region near the thermodynamic critical point for thermal conductivity and a large region (573 to 647.3 K) for viscosity. For these regions, the tabulated values of references 1 and 2 represent the output of some interpolation scheme. However, no technique for predicting transport properties in these regions is given in these references.

Viscosity and Thermal Conductivity

Reference 8 uses the simple empirical technique of reference 9 to express the viscosity η and thermal conductivity λ of several fluids. An excess function of density ρ is added to the dilute gas function of temperature T such that

$$\eta = \eta_1 + \Delta\eta \tag{4}$$

$$\Delta\eta = \eta - \eta_1 = F(\rho) \tag{5}$$

$$\eta_1 = F(T) \qquad \text{at } P = 0.1 \text{ MN/m}^2 \tag{6}$$

and

$$\lambda = \lambda_1 + \Delta\lambda \tag{7}$$

$$\Delta\lambda = \lambda - \lambda_1 = F(\rho) \tag{8}$$

$$\lambda_1 = F(T) \qquad \text{at } P = 0.1 \text{ MN/m}^2 \tag{9}$$

We used this technique to obtain viscosity and thermal conductivity in the regions where no equation existed in references 1 and 2.

The $\Delta\eta$'s shown in figure 1 were obtained from the tabulated and computed data in references 1 and 2. These data were then extrapolated through the region where no fit is available (region 4) to predict the viscosity in that region.

Figure 1 gives a good representation for viscosity over a considerably larger range than 573 to 647.3 K, with deviations from the tabulated data up to 7 percent in some regions and perhaps 10 percent in the critical region. References 1 and 2 list uncertainties at ±4 percent in those regions where the values were not interpolated, and no uncertainties are given for the interpolated region. The analytical representations of viscosity are given in appendix B.

The $\Delta\lambda$'s used to predict thermal conductivity were also obtained from the tabulated and computed data of references 1 and 2. In this case the scatter is more acute

over a wide range of density because these data are pressure sensitive and are not entirely represented by excess thermal conductivity as a function of density, see figure 2. While the curve of figure 2 represents a wider P, T range than the region where no curve fit is available (region V) in figure 2, the $\Delta\lambda$ curve fit is used only in region V.

Generally, deviations to 8 percent in λ-calculations can be found with respect to the tabulated data. References 1 and 2 give the deviations as ±4 percent in regions where curve fits exist, and no uncertainties are listed for the interpolated region. The analytic forms for thermal conductivity are given in appendix B. In region IV (fig. 2) the implicit equation for thermal conductivity from reference 2 is used. In region III an explicit expression for thermal conductivity from reference 2 is used. These forms were adopted over those of reference 1 because of their analytic nature.

The 0.1-MN/m^2 thermal conductivity and viscosity output from 700 to 1700 K was checked against the results of Svehla (ref. 10). Svehla's viscosity is 5 to 10 percent higher and his thermal conductivity is 10 to 15 percent higher than those predicted herein. Since the publishing of reference 10, Svehla has found that inclusion of a rotational relaxation effect would lower his calculated viscosity perhaps 5 percent, and lower his calculated thermal conductivity perhaps 10 to 15 percent.

Near-Critical Thermal Conductivity

The anomalous behavior of thermal conductivity in the near-critical region was measured by Le Neindre (ref. 11). Sengers (ref. 12) advanced a technique to predict the behavior of near-critical thermal conductivity data for carbon dioxide. In reference 13, Sengers' technique was modified, extended to several fluids, and compared with other methods. The technique used herein is the same as Sengers' technique as presented in reference 13, except that the proportionality constant, 3.05×10^{-5} as given by Sengers in reference 12, has been increased to 11.6×10^{-5}.

THERMODYNAMIC AND TRANSPORT PROPERTY PLOTS

Sample plots of the properties calculated by WASP are found in figures 3 to 14.[3] The triple temperature scales in these figures are to facilitate checking. Figure 3 represents density as a function of temperature for selected isobars, including the critical isobar. No irregularities were found. Figure 4(a) represents the pressure as a function of temperature for selected isochores. These isochores exhibit distinct curvature not only near the saturation boundaries but in the extended regions as well. The slopes

[3]Isobars which cross the saturation boundaries are parallel to isotherms. The plotting routine simply connects increments in temperature.

of the isochores as a function of temperature are shown in figure 4(b), which reveals the nonlinear character of most of the isochores of figure 4(a). Figure 5 represents the pressure-volume (P-V) plane for selected isotherms. Local P-V regions could be mapped by using WASP for preliminary cycle analysis. Figure 6 represents enthalpy as a function of temperature for selected isobars, including the critical isobar. Figure 7 represents the temperature-entropy (T-S) diagram for selected isobars. Again, local T-S regions could be mapped by using WASP for preliminary cycle analysis.

Figure 8 represents specific heat at constant pressure and figure 9(a) represents specific heat at constant volume for selected isobars, including the critical isobar. Note the peaking effects in C_v along the critical isobar; this indicates a discontinuity in C_v, as well as in C_p, along the critical isobar. This behavior agrees with the most recent thinking on C_v in the critical region; namely, that C_v possesses a weak logarithmic infinity (i.e., $C_v \propto |T - T_c|^{-0.06}$, as discussed in ref. 14). In figure 9(b), the isentropic expansion coefficient ($\gamma = C_p/C_v$) is given as a function of temperature for selected isobars, including the critical isobar. Note that while C_p and C_v tend toward a discontinuity, so also does the ratio. The reason is that C_p possesses a very strong "infinity" at the critical point $\left(C_p \propto \left|T - T_c\right|^{-\beta_1}\right.$, where $\left.1.2 < \beta_1 < 1.35\right)$ and C_v a rather weak "infinity." Consequently, in the critical region, γ diverges approximately as $\left|T - T_c\right|^{-\beta_2}$, where $1.1 < \beta_2 < 1.3$.

Figure 10 gives sonic velocity as a function of temperature for selected isobars. Sonic velocity tends toward zero, or at least a minimum, in the critical region C_c, which also concurs with recent thinking because

$$C_c \propto \frac{1}{\rho}\sqrt{\frac{T}{C_v}}\left(\frac{\partial P}{\partial T}\right)_\rho$$

Since C_v diverges in a weak manner and $(\partial P/\partial T)_\rho$ is nonzero and finite, C_c will approach zero in a weak manner.

Figure 11 represents a plot of viscosity as a function of temperature along selected isobars, including the critical isobar. The discontinuities of this surface at 573 and 647 K are caused by the empirical nature of the curve fit (fig. 1), as discussed previously. This discontinuity is on the average less than 4 percent, which is the same order of accuracy as presented in references 1 and 2.

Figure 12(a) represents thermal conductivity as a function of temperature along selected isobars. In this report, an attempt has been made to include the anomalous behavior of thermal conductivity in the near-critical regions based on references 12, 13, 15, and 16. The behavior of the near-critical thermal conductivity is shown in figure 12(b). In order for the user to obtain these values, he must add EXCESSK, which represents the anomalous part of the thermal conductivity, to the normally computed

value of thermal conductivity. See USER'S GUIDE TO WASP, the statement COMMON/ PROPTY/ . . . . Generally, the plots of η and λ exhibit some irregularities where the various predicting techniques overlap; however, for most applications the values returned are within acceptable tolerance.

Figure 13 is a plot of surface tension σ and Laplace constant as a function of temperature. Metastable conditions near both the liquid and vapor are often required in a system analysis and can be calculated by equation (1). A special subroutine is included in appendix G which when used with WASP will give metastable properties; sample plots are shown as figure 14.

Other Thermodynamic Functions

WASP provides sufficient PVT and derived property data for most users; however, if other functions are required, the user may calculate these by using the partial derivatives $(\partial P/\partial \rho)_T$ and $(\partial P/\partial T)_\rho$, along with the other results from WASP. Appendix H is provided to give the user a handy reference to the so-called Bridgeman Tables which list most of the interrelations between thermodynamic variables. (See pp. 36 and 64.)

Comparison Plots

Of utmost importance is how well equation (1), as used in WASP, agrees with the International Skeleton Tables for steam and water (refs. 1 and 2). Figures 15 to 17 were obtained by running all the data points listed in table 1. 2 of reference 1 (see also table 4b of ref. 2) on each of the three input options (T, P), (ρ, T), and (ρ, P) in WASP. Each of the figures is discussed, but the careful reader should note that discrepancies exist in the specific volumes presented in these two references. The authors noted four obvious errors in reference 2 by comparing references 1 (table 1. 2) and 2 (table 4b). Reference 1 was assumed to be correct. Other discrepancies occur in reference 2, for instance in the specific heat C_p. No attempt was made to track all these errors, and the reader should use reference 2 cautiously.

Figure 15 represents the percent relative error in density, $[(\rho_{table} - \rho_{calc})/\rho_{table}] \times 100$, as a function of density. With the exception of three points, all the values are within +0. 25 percent and -0. 50 percent, and generally have an error of less than 1 part in 3000. The solution for density is iterative, and perhaps the error could be reduced somewhat by a tightening of the convergence criteria. This is not recommended for two reasons: (1) It will require a great increase in computer time, and (2) errors in these printed tables have been noted. The tolerance should be quite satisfactory to all but the most critical user.

Figure 16 represents the percent relative error in pressure, $[(P_{table} - P_{calc})/P_{table}] \times 100$, as a function of pressure. In all cases the calculated pressures are within +3.0 percent and -2.0 percent of the tabulated value; most points lie within +0.25 percent of the tabulated value. The prediction of pressure at high density (low temperatures) using a fundamental equation or a state equation is quite difficult. These pressure errors are all within accepted tolerances.

Figure 17 represents the percent relative error in temperature, $[(T_{table} - T_{calc})/T_{table}] \times 100$, as a function of temperature. With the exception of about a dozen points, the predicted temperatures are within +0.25 percent and -0.4 percent and generally lie within ±0.1 percent.

Usually, temperature and density are predictable because of the manner in which the data were acquired; however, pressure is always difficult to calculate. With these basic guidelines in mind and figures 15 to 17, it can be said that the equation gives a faithful representation of the International Skeleton Tables (refs. 1 and 2).

USER'S GUIDE TO WASP

The user with limited programming experience should have no difficulty in following the operating instructions for WASP. After gaining a little experience with WASP, the only references needed are table I (the operations sheet) and table II (the units specification).

How WASP Handles Input/Output

WASP is a group of subroutines designed to be used as a subprogram with the user's program. Standard communication between the user's program and WASP is achieved by the following two FORTRAN statements, which contain the symbols representing the input/output parameters and options:

```
COMMON/PROPTY/KU, DL, DV, HL, HV, etc.
CALL WASP (KS, KP, T, P, D, H, KR)
```

See table I and appendix A.

Three requirements must be fulfilled for a successful call to WASP:

(1) The cards for COMMON/PROPTY/KU, DL, DV, etc., must be included in the user's main program or the subroutine that calls WASP. The WASP subprogram deck must be correctly loaded with the user's program as shown in table III. The variables MU, MUL, MUV, K, KL, and KV must be declared REAL. (K cannot be used as an

index for a subscripted variable.) However, the user can change the names of these variables in COMMON/PROPTY/KU, DL, DV, etc., ...

(2) The units system for input/output must be correctly specified. KU is an input control specified in the COMMON/PROPTY/KU, DL, DV, etc., which must be set such that $1 \leq KU \leq 5$. KU identifies the units system for input/output, and KU is never altered by WASP. Therefore, unless the user switches from one system to another, he need set his value for KU only once, before any calls to subroutine WASP.

There are three specified units options described in table II. The option KU=1 is the internal program units system. The other two options are commonly used in engineering calculations. If the user does not wish to use one of these options, he can specify any desired units system for KU=4 and KU=5, provided the conversion factors for this system are stored by the user as directed in table II.

(3) The controls KR, KS, and KP, which tell WASP what variables are to be used as input and what properties are requested for output, must be correctly initialized in the call statement for subroutine WASP. The corresponding input variables in the call statement and COMMON/PROPTY/ . . . must also be correctly initialized.

KS and KR are controls that determine which of the variables T, P, D, H, or S or combinations thereof are needed as thermodynamic input. KP is an input control which specifies which properties are sought as output.

KR is also an output variable since it gives the correct region number for the variables in a specific call to WASP, as shown in the sketch in table I. Depending on the input for KS and KP, the other possible output variables are T, P, D, H, and all of COMMON/PROPTY/ except the control KU.

As mentioned above, KR is both input and output and must be reset before each call to WASP. The input options are

(a) KR=0 when user wishes WASP to determine a value for KR

(b) KR=1 when user wishes saturation conditions[4]

The output for KR will be

(a) KR=1 for saturation

(b) KR=2 for liquid

(c) KR=3 for vapor

KS specifies which variables are to be used as input for a call to subroutine WASP. (In the remaining discussion on WASP input/output, the input variables are assumed to be in user's units specified by KU. Output is always returned in the KU system of units.)

[4]Saturation or coexistence conditions exist on the PVT surface when pressure is a function of only temperature and the liquid and vapor states both exist at that pressure. Thus when KR=1, two outputs for each property are available in COMMON/PROPTY/ and only one independent variable is required for some input options, as shown in the KS-KR input/output chart.

The following table shows the input and output for all KS, KR combinations:

Thermodynamic region specification, KR	State relation specification, KS				
	1	2	3	4	5
	Input				
0	T and P	T and D	P and D	P and H	P and S
1	T or P[a]	T	P	P	P
	Output				
1	T or P[a], DL and DV	P	T	T, DL, DV	T, DL, DV
2	D	P	T	D and T	D and T
3	D	P	T	D and T	D and T

[a]If T is the desired input, set P = 0.0 prior to the call and vice versa. Then WASP will return the correct saturation value for the 0.0 input. If both T and P have an input value ≠ 0.0, WASP uses T but will not alter P input.

KP is an input control that specifies which derived and transport properties are requested by the user. It is the sum of the individual KP options and is described in table I. This binary sum allows WASP to uniquely identify any combination of requests. The following table shows the output locations for the specific KR and KP combinations:

Value added to KP input	Output for KR=2 or 3	Output for KR=1		Name of calculated property
		Liquid	Vapor	
0	---	---	---	None requested
1	H	HL	HV	Enthalpy
2	S	SL	SV	Entropy
4	CP	CPL	CPV	Specific heat at constant pressure
	CV	CVL	CVV	Specific heat at constant volume
	GAMMA	GAMMAL	GAMMAV	Specific-heat ratio
	C	CL	CVP	Sonic velocity
8	MU	MUL	MUV	Viscosity
16	K	KL	KV	Thermal conductivity
32	SIGMA	SIGMA	---	Surface tension of the liquid as a function of temperature
	ALC	ALC	---	Laplace constant as a function of temperature

Troubleshooting for User Errors

After experience with WASP, we have found that several common errors are easily detected and corrected.

(1) Failure to set $1 \leq KU \leq 5$ will cause a "division by 0.0" and/or no valid answers. Set KU to its proper value.

(2) Failure to set $1 \leq KS \leq 5$ will most likely cause a halt to the program because of an execution error. The branching on KS in subroutine WASP is a computed "GO TO." Simply set KS to its proper value.

(3) Failure to set KP will return enthalpy if KP is odd and no derived properties if KP is even.

(4) If a wrong value is entered for KR, it is treated as KR=0. If a user enters KR=1 when he does not want saturation properties, he will get them anyway for $T < T_c$ and otherwise will get a wrong answer.

(5) If any T, P, D, H, or S is entered incorrectly, that value will be used and the answer will be wrong.

(6) If the COMMON/PROPTY/ is duplicated incorrectly, there are a variety of possible errors, almost all serious.

Other small problems may be encountered if WASP is modified for different compilers or computers. The FORTRAN IV coding in WASP is machine independent except for a few Hollerith format statements which can be easily changed. The reader who needs more detailed information should read the appendixes.

Additional Information

The approximate core storage for the complete WASP program is $(14650)_8 = (6568)_{10}$ locations.

The time estimates were obtained by running an average of 100 calls over the entire PVT range for each option indicated. The shortest call was for pressure, KS=2, at an average of 4 milliseconds per call for $T > T_c$ and 17 milliseconds for $T \leq T_c$. The call for density, KS = 1, varied from 17 to 40 milliseconds for all regions, with the greatest time being consumed in the near-critical region. The call for temperature, KS=3, varied from 11 to 70 milliseconds per call, with the least time used when $P > P_c$ and the most time used in the near-critical region. The call for density and all the derived properties, KS=1 and KP=63, varied from 38 to 120 milliseconds per call depending on the density call and the regions for the transport properties.

The P, H and P, S calls, KS=4 and KS=5, each required from 300 to 800 milliseconds per call, with the greatest time in the near-critical region. These results are summarized as follows:

State relation specification, KS					
1	2	3	4	5	1
Thermodynamic and transport properties specification, KP					
0	0	0	0	0	63
Time, msec/call					
17 to 40	4 to 17	11 to 70	300 to 800	300 to 800	38 to 120

Problems Previously Encountered When Converting to Non-IBM Machines or Different FORTRAN IV - FORTRAN V Compilers

The problems encountered in converting to different equipment are as follows:

(1) IBM 360 users should run in double precision by inserting implicit REAL*8 (A-H, O-Z) and REAL*8 MU, MUL, MUV, K, KL, KV in subroutine WASP and implicit REAL*8 (A-H, O-Z) in all other subroutines. Change COMMON/PROPTY/KU, KZ, DL, DV, etc., for proper alinement.

(2) Data statements are found in subroutines BLOCK DATA, THERM, VISC, and SURF. Many compilers differ in formating data statements.

(3) The multiple-entry routine (CHECK, TCHECK, PCHECK, DCHECK) has an entry point, DCHECK, whose input vector (KU, D) does not correspond in kind and number with the other entry points (KU, KR, T) or (KU, KR, P). To our knowledge this has caused a problem on only one compiler, a FORTRAN IV for a CDC 3800. It was easily remedied by an equivalence statement.

The authors adapted the code to fit the following compilers and machines: UNIVAC 1108, CDC 3600, CDC 6600, IBM 360/67TSS, and IBM 7094-7044 DCS.

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National Aeronautics and Space Administration,
Cleveland, Ohio, April 26, 1973,
502-04.

APPENDIX A

SYMBOLS

Mathematical symbol	FORTRAN symbol[5]	Definition
A_{ij}	A(I, J)	coefficients of terms in Q-function (see table IV)
	ALC	Laplace constant
c	C	sonic velocity, cm/sec
	CL	sonic velocity of saturated liquid, cm/sec
	CVP	sonic velocity of saturated gas, cm/sec
C_1 . . . C_5	SIC1 . . . SIC5	coefficients of terms in ψ_0 function (see table IV)
C_p	CP	specific heat at constant pressure, J/(g)(K)
	CPL	specific heat C_p of saturated liquid, J/(g)(K)
	CPV	specific heat C_p of saturated vapor, J/(g)(K)
C_v	CV	specific heat at constant volume, J/(g)(K)
	CVL	specific heat C_v of saturated liquid, J/(g)(K)
	CVV	specific heat C_v of saturated vapor, J/(g)(K)
D_1 . . . D_7	CPS1 . . . CPS7	coefficients for vapor pressure curve (see table IV)
E	E	E = 4.8
H	H	enthalpy, J/g
	HL	enthalpy of saturated liquid, J/g

[5]Symbols used in each individual subroutine are identified in that subroutine (see appendix C).

	HV	enthalpy of saturated vapor, J/g
	KP	thermodynamic and transport properties specification
	KR	thermodynamic region specification
	KS	state relation specification
	KU	units specification
P	P	pressure, MN/m^2
Q	QCALC	data-fitting function
R	R	specific gas constant for water, 0.46151 J/(g)(K)
S	S	entropy, J/(g)(K)
	SL	entropy of saturated liquid, J/(g)(K)
	SV	entropy of saturated vapor, J/(g)(K)
T	T	temperature, K
u		internal energy, J/g
γ	GAMMA	ratio of specific heats, C_p/C_v
	GAMMAL	ratio of specific heats for saturated liquid
	GAMMAV	ratio of specific heats for saturated vapor
η	MU	dynamic viscosity, g/(cm)(sec)
	MUL	dynamic viscosity of saturated liquid, g/(cm)(sec)
	MUV	dynamic viscosity of saturated vapor, g/(cm)(sec)
λ	K	thermal conductivity, W/(cm)(K)
	KL	thermal conductivity of saturated liquid, W/(cm)(K)
	KV	thermal conductivity of saturated vapor, W/(cm)(K)
ρ	D	density, g/cm^3
ρ_L	DL	density of saturated liquid, g/cm^3
ρ_V	DV	density of saturated vapor, g/cm^3
ρ_a	RHOA	constant used in Q-function, $\rho_a = 0.634$
ρ_b	RHOB	constant used in Q-function, $\rho_b = 1.0$
σ	SIGMA	surface tension, dyne/cm
$\tau = \frac{1000}{T}$	TAU	temperature parameter, K^{-1}

τ_a	TAUA	constant used in Q-function, $\tau_a = 2.5$
τ_c	TAUC	1000 divided by critical temperature expressed in kelvin
ψ	PSI	Helmholtz free energy, J/g
ψ_0	PSI0	reference function, J/g
$\dfrac{d\psi_0}{dT}$	PSIT	
$\left(\dfrac{\partial Q}{\partial \tau}\right)_\rho$	QTD	
$\left(\dfrac{\partial Q}{\partial \rho}\right)_\tau$	QDT	
$\left(\dfrac{\partial^2 Q}{\partial \tau^2}\right)_\rho$	Q2T2D	partial derivatives used in evaluating ψ and its derivatives
$\left(\dfrac{\partial^2 Q}{\partial \rho^2}\right)_\tau$	Q2D2T	
$\dfrac{\partial^2 Q}{\partial \tau\, \partial \rho}$	Q2DT	

APPENDIX B

PROPERTY EQUATIONS OF WASP

The equations used in WASP were those taken from Keyes, Keenan, Hill, and Moore (ref. 3), Schmidt (ref. 2) and the ASME Steam Tables (ref. 1) and those developed by the authors.

FUNDAMENTAL EQUATION

The basic equation of WASP expresses the Helmholtz free energy in terms of ρ and T,

$$\psi = \psi(\rho, T) \tag{B1}$$

whereas the equation of state is usually expressed as

$$P = P(\rho, T) \tag{B2}$$

Equation (B1) is complete inasmuch as the required thermodynamic functions are derivatives of ψ and undetermined constants and/or functions are not required. For example, specific heat at "zero" pressure C_{p_0}, which is a function of temperature, is not required in the ψ-form; however, in the P-form (eq. (B2)), C_{p_0} is required to obtain entropy, enthalpy, and specific heats.

When equation (B1) is expanded, ψ becomes

$$\psi = \psi_0(T) + RT[\ln \rho + \rho Q(\rho, \tau)] \tag{B3}$$

where

$$Q = \sum_{i=1}^{8} A_{i1}(\rho - \rho_a)^{i-1} + e^{-E\rho}(A_{9,1} + A_{10,1}\rho)$$
$$+ (\tau - \tau_c)\left\{\sum_{j=2}^{7} (\tau - \tau_a)^{j-2}\left[\sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho)\right]\right\} \tag{B4}$$

$$\psi_0(T) = C_1 + C_2 T + C_3 T^2 + (C_4 + C_5 T)\ln T \tag{B5}$$

$$\tau = \frac{1000}{T}\ K^{-1} \tag{B6}$$

$$\left.\begin{aligned}
\rho_a &= 0.634\ g/cm^3 \\
\rho_b &= 1.0\ g/cm^3 \\
\tau_a &= 2.5\ K^{-1} \\
\tau_c &= 1.544912\ K^{-1} \\
E &= 4.8\ cm^3/g \\
R &= 0.46151\ J/(g)(K)
\end{aligned}\right\} \tag{B7}$$

and the constants $C_1, \ldots, C_5$ and A_{ij} are given in table IV.

DERIVATIVES OF Q

The derivatives of Q are required to evaluate any of the thermodynamic properties:

$$\left(\frac{\partial Q}{\partial \tau}\right)_\rho = \left\{\sum_{j=2}^{7} (\tau - \tau_a)^{j-2} \left[\sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho)\right]\right\}$$

$$+ (\tau - \tau_c)\left\{\sum_{j=3}^{7} (j - 2)(\tau - \tau_a)^{j-3} \left[\sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho)\right]\right\} \tag{B8}$$

$$\left(\frac{\partial Q}{\partial \rho}\right)_\tau = \sum_{i=2}^{8} (i - 1)A_{i1}(\rho - \rho_a)^{i-2} + e^{-E\rho}\left[- E(A_{9,1} + A_{10,1}\rho) + A_{10,1}\right]$$

$$+ (\tau - \tau_c)\left(\sum_{j=2}^{7} (\tau - \tau_a)^{j-2}\left\{\sum_{i=2}^{8} (i - 1)A_{ij}(\rho - \rho_b)^{i-2} + e^{-E\rho}\left[- (A_{9j} + A_{10j}\rho)E + A_{10j}\right]\right\}\right) \tag{B9}$$

$$\frac{\partial^2 Q}{\partial\rho\,\partial\tau} = \sum_{j=2}^{7} (\tau - \tau_a)^{j-2}\left[\sum_{i=2}^{8} (i - 1)A_{ij}(\rho - \rho_b)^{i-2} + e^{-E\rho}(- EA_{9j} - E\rho A_{10j} + A_{10j})\right]$$

$$+ (\tau - \tau_c)\left\{\sum_{j=3}^{7} (j - 2)(\tau - \tau_a)^{j-3}\left[\sum_{i=2}^{8} (i - 1)A_{ij}(\rho - \rho_b)^{i-2} + e^{-E\rho}(- EA_{9j} - EA_{10j}\rho + A_{10j})\right]\right\}$$

(B10)

$$\left(\frac{\partial^2 Q}{\partial\rho^2}\right)_\tau = \sum_{i=3}^{8} A_{i1}(i - 1)(i - 2)(\rho - \rho_a)^{i-3} + e^{-E\rho}\left\{\left[- EA_{9,1} + A_{10,1}(2 - E\rho)\right](- E)\right\}$$

$$+ (\tau - \tau_c)\left(\sum_{j=2}^{7} (\tau - \tau_a)^{j-2}\left\{\sum_{i=3}^{8} A_{ij}(i - 1)(i - 2)(\rho - \rho_b)^{i-3} + e^{-E\rho}\left[- EA_{9j} + A_{10j}(2 - E\rho)\right](- E)\right\}\right)$$

(B11)

$$\left(\frac{\partial^2 Q}{\partial\tau^2}\right)_\rho = 2\left\{\sum_{j=3}^{7} (j - 2)(\tau - \tau_a)^{j-3}\left[\sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho)\right]\right\}$$

$$+ (\tau - \tau_c)\left\{\sum_{j=4}^{7} (j - 2)(j - 3)(\tau - \tau_a)^{j-4}\left[\sum_{i=1}^{8} A_{ij}(\rho - \rho_b)^{i-1} + e^{-E\rho}(A_{9j} + A_{10j}\rho)\right]\right\}$$

(B12)

THERMODYNAMIC PROPERTIES

The derivatives of ψ give all the functions necessary to obtain the thermodynamic properties.

Pressure and Its Derivatives

$$P = \rho^2\left(\frac{\partial\psi}{\partial\rho}\right)_T = \rho^2\left(\frac{\partial\psi}{\partial\rho}\right)_\tau = \rho R\,\frac{1000}{\tau}\left[1 + \rho Q + \rho^2\left(\frac{\partial Q}{\partial\rho}\right)_\tau\right] \qquad \text{(B13)}$$

$$\left(\frac{\partial P}{\partial \rho}\right)_\tau = \frac{1000\ R}{\tau}\left[1 + 2\rho Q + 4\rho^2\left(\frac{\partial Q}{\partial \rho}\right)_\tau + \rho^3\left(\frac{\partial^2 Q}{\partial \rho^2}\right)_\tau\right] \tag{B14}$$

$$\left(\frac{\partial P}{\partial \tau}\right)_\rho = \frac{-1000}{\tau^2}\left(\rho R\left[1 + \rho Q + \rho^2\left(\frac{\partial Q}{\partial \rho}\right)_\tau\right] - R\rho\tau\left\{\rho\left[\left(\rho\frac{\partial^2 Q}{\partial \tau\ \partial \rho}\right) + \left(\frac{\partial Q}{\partial \tau}\right)_\rho\right]\right\}\right) \tag{B15}$$

$$\left(\frac{\partial P}{\partial T}\right)_\rho = -\left(\frac{\partial P}{\partial \tau}\right)_\rho \frac{\tau^2}{1000} \tag{B16}$$

Enthalpy and Its Derivatives

$$H = u + \frac{P}{\rho} \tag{B17}$$

$$H = \left[\frac{\partial(\psi\tau)}{\partial \tau}\right]_\rho + \frac{P}{\rho} \tag{B18}$$

$$H = \left[\psi_0 + 1000\ R\rho\left(\frac{\partial Q}{\partial \tau}\right)_\rho - T\frac{d\psi_0}{dT}\right] + \frac{1000\ R}{\tau}\left[1 + \rho Q + \rho^2\left(\frac{\partial Q}{\partial \rho}\right)_\tau\right] \tag{B19}$$

where the first term of equation (B19) is the internal energy u.

$$H = \frac{1000\ R}{\tau}\left\{1 + \rho\left[Q + \tau\left(\frac{\partial Q}{\partial \tau}\right)_\rho + \rho\left(\frac{\partial Q}{\partial \rho}\right)_\tau\right]\right\} + \psi_0 - T\frac{d\psi_0}{dT} \tag{B20}$$

$$\left(\frac{\partial H}{\partial T}\right)_\rho = - T\frac{d^2\psi_0}{dT^2} + R\left[1 + \rho Q + \rho^2\left(\frac{\partial Q}{\partial \rho}\right)_\tau - \tau\rho\left(\frac{\partial Q}{\partial \tau}\right)_\rho - \tau\rho^2\frac{\partial^2 Q}{\partial\tau\,\partial\rho} - \rho\tau^2\left(\frac{\partial^2 Q}{\partial\tau^2}\right)_\rho\right] \quad \text{(B21)}$$

$$\left(\frac{\partial H}{\partial \rho}\right)_T = \frac{1000\ R}{\tau}\left\{Q + \tau\left[\left(\frac{\partial Q}{\partial \tau}\right)_\rho + \rho\frac{\partial^2 Q}{\partial\rho\,\partial\tau}\right] + \rho\left[3\left(\frac{\partial Q}{\partial \rho}\right)_\tau + \rho\left(\frac{\partial^2 Q}{\partial\rho^2}\right)_\tau\right]\right\} \quad \text{(B22)}$$

Entropy

$$S = -\left(\frac{\partial\psi}{\partial T}\right)_\rho \quad \text{(B23)}$$

$$S = - R\left\{\ln\rho + \rho\left[Q - \tau\left(\frac{\partial Q}{\partial\tau}\right)_\rho\right]\right\} - \frac{d\psi_0}{dT} \quad \text{(B24)}$$

Specific Heats

Constant volume:

$$C_v = \left(\frac{\partial u}{\partial T}\right)_\rho \quad \text{(B25)}$$

$$C_v = -\left[R\rho\tau^2\left(\frac{\partial^2 Q}{\partial\tau^2}\right)_\rho + T\frac{d^2\psi_0}{dT^2}\right] \quad \text{(B26)}$$

Constant pressure:

$$C_p = \left(\frac{\partial H}{\partial T}\right)_\rho - \left(\frac{\partial H}{\partial \rho}\right)_T\left[\frac{\left(\frac{\partial P}{\partial T}\right)_\rho}{\left(\frac{\partial P}{\partial \rho}\right)_T}\right] \quad \text{(B27)}$$

"Isentropic" expansion coefficient:

$$\gamma = \frac{C_p}{C_v} \tag{B28}$$

Sonic Velocity

$$C^2 = \left(\frac{\partial P}{\partial \rho}\right)_S \tag{B29}$$

$$C^2 = \gamma\left(\frac{\partial P}{\partial \rho}\right)_T \tag{B30}$$

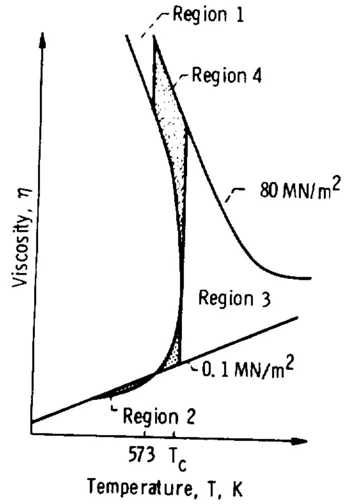
Vapor Pressure Curve

$$\log_{10} P = (1 + D_1) + \sum_{j=3}^{7} D_j(T - 273.15)^j + \frac{D_2}{T - 273.15} \tag{B31}$$

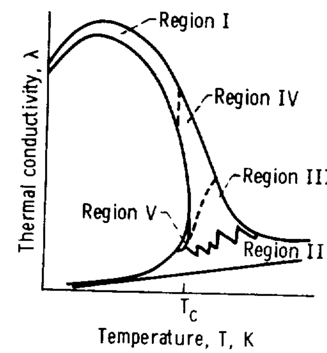
where the original data are in bars and $^{\circ}C$ whereas pressure and temperature in the program are in MN/m^2 and K, hence the forms $(1 + D_1)$ and $(T - 273.15)$.

TRANSPORT PROPERTIES

The transport property equations are not as concisely defined as the fundamental equation. The transport maps for viscosity and thermal conductivity are broken into several regions, as shown in sketches a and b, respectively, and individual curve fits are presented for each. Also, several regions are void of description as they exist in references 1 and 2.



(a)



(b)

Viscosity

Atmospheric pressure. - For $P = 0.1\ \mathrm{MN/m^2}$ and $373.15\ \mathrm{K} < T < 973.15\ \mathrm{K}$,

$$\eta_1 = \left[b_1\left(\frac{T}{T_c} - b_2\right) + b_3\right] \times 10^{-6} \tag{B32}$$

Region 1. - For $P_{sat} < P < 80\ \mathrm{MN/m^2}$ and $273.15\ \mathrm{K} < T < 573.15\ \mathrm{K}$,

$$\eta = 10^{-6}\, a_1 \left[1 + \left(\frac{\rho}{\rho_c} - \frac{P_{sat}}{P_c}\right) \times a_4\left(\frac{T}{T_c} - a_5\right)\right] \times 10^{\left[\frac{a^2}{(T/T_c) - a_3}\right]} \tag{B33}$$

Region 2. - For $0.1\ \mathrm{MN/m^2} < P < P_{sat}$ and $373.15\ \mathrm{K} < T < 573.15\ \mathrm{K}$,

$$\eta = \left\{\eta_1 \times 10^6 - 10\,\frac{\rho}{\rho_c}\left[c_1 - c_2\left(\frac{T}{T_c} - c_3\right)\right]\right\} \times 10^{-6} \tag{B34}$$

Region 3. - For $0.1\ \mathrm{MN/m^2} < P < 80\ \mathrm{MN/m^2}$ and $648.15\ \mathrm{K} < T < 1073.15\ \mathrm{K}$,

$$\eta = \left[\eta_1 \times 10^6 + d_3\left(\frac{\rho}{\rho_c}\right)^3 + d_2\left(\frac{\rho}{\rho_c}\right)^2 + d_1\left(\frac{\rho}{\rho_c}\right)\right] \times 10^{-6} \tag{B35}$$

Region 4. - Tabulated values of viscosity in region 4, as well as computed values of viscosity at equivalent densities, were plotted as per figure 1. The resulting curve gives an accurate representation of these data, with the exception of those values along the saturation locus in the near-critical region. As can be seen, deviations of up to 7 percent, and 10 percent at the critical point, are common.

$$\left.\begin{aligned} k &= 1 \qquad \text{for } \rho/\rho_c \leq 4/3 \\ k &= 2 \qquad \text{for } \rho/\rho_c > 4/3 \end{aligned}\right\} \tag{B36}$$

$$\eta = \eta_1 + \frac{10^Y}{0.0192} \tag{B37}$$

where

$$Y = C_{5k}X^4 + C_{4k}X^3 + C_{3k}X^2 + C_{2k}X + C_{1k} \tag{B38}$$

$$X = \log_{10}\left(\frac{\rho}{\rho_c}\right) \tag{B39}$$

The following coefficients are used in the viscosity equations:

$a_1 = 241.4$

$a_2 = 0.3828209486$

$a_3 = 0.2162830218$

$a_4 = 0.1498693949$

$a_5 = 0.4711880117$

$b_1 = 263.4511$

$b_2 = 0.4219836243$

$b_3 = 80.4$

$c_1 = 586.1198738$

$c_2 = 1204.753943$

$c_3 = 0.4219836243$

$d_1 = 111.3564669$

$d_2 = 67.32080129$

$d_3 = 3.205147019$

$$C_{1k} = -6.4556581$$

$$C_{2k} = 1.3949436$$

$$C_{3k} = 0.30259083$$

$$C_{4k} = 0.10960682$$

$$C_{5k} = 0.015230031$$

For $k = 2$,

$$C_{1k} = -6.4608381$$

$$C_{2k} = 1.6163321$$

$$C_{3k} = 0.07097705$$

$$C_{4k} = -13.938$$

$$C_{5k} = 30.119832$$

Thermal Conductivity

Atmospheric pressure. - For $P = 0.1\ MN/m^2$ and $373.15\ K < T < 973.15\ K$,

$$\lambda_1 = (17.6 + 0.0587\ t + 1.04\times10^{-4}\ t^2 - 4.51\times10^{-8}\ t^3) \times 10^{-5} \tag{B40}$$

where

$$t = T - 273.15 \tag{B41}$$

Region I. - For $P_{sat} < P < 50.0\ MN/m^2$ and $273.15\ K < T < 623.15\ K$,

$$\lambda = \left\{S_1 + \left(\frac{P - P_{sat}}{P_c}\right)\left[S_2 + \left(\frac{P - P_{sat}}{P_c}\right)S_3\right]\right\} \times 10^{-2} \tag{B42}$$

where

$$S_1 = \sum_{i=0}^{4} a_i\left(\frac{T}{T_c}\right)^i \qquad \text{(B43)}$$

$$S_2 = \sum_{i=0}^{3} b_i\left(\frac{T}{T_c}\right)^i \qquad \text{(B44)}$$

$$S_3 = \sum_{i=0}^{3} c_i\left(\frac{T}{T_c}\right)^i \qquad \text{(B45)}$$

Region II. - For the following ranges of pressure (in MN/m^2) and temperature (in K):

$$0.1 < P \leq 17.5 \text{ and } T_{sat} < T < 973.15$$

$$17.5 < P \leq 22.5 \text{ and } 673.15 < T < 973.15$$

$$22.5 < P \leq 27.5 \text{ and } 698.15 < T < 973.15$$

$$27.5 < P \leq 35.0 \text{ and } 723.15 < T < 973.15$$

$$35.0 < P \leq 45.0 \text{ and } 773.15 < T < 973.15$$

$$45.0 < P \leq 50.0 \text{ and } 823.15 < T < 973.15$$

thermal conductivity is

$$\lambda = \left[\lambda_1 + (103.51 + 0.4198\ t - 2.771\times10^{-5}\ t^2)\rho + \frac{2.1482\times10^{14}}{t^{4.2}}\rho^2\right]\times10^{-5} \qquad \text{(B46)}$$

where

$$t = T - 273.15 \qquad \text{(B47)}$$

Region III. - If the (P, T) is not in region II (see eq. (B54)) but $P < 50\ MN/m^2$ and 373.15 K < T < 973.15 K, then the following should be used:

$$\lambda = \frac{A\left(\frac{T}{T_c}\right)^{1.445}}{1 - Bd_{31}\left(\frac{T}{T_c}\right)^{-7}} + \frac{d_{32}\left(\frac{P}{P_c}\right)^4 \exp\left[-9d_{33}\left(\frac{T}{T_c} - 1\right)\right]}{1 + d_{34}\left(\frac{P}{P_c}\right)^{-12}} \times \left\{d_{35} - d_{36}\left(\frac{P}{P_c}\right)\exp\left[-d_{33}\left(\frac{T}{T_c} - 1\right)\right]\right\} \tag{B48}$$

$$A = a_{31}\left(\frac{P}{P_c}\right) + a_{32} \tag{B49}$$

$$B = \frac{b_{31}\left(\frac{P}{P_c}\right)^{1.63}}{1 + b_{32}\left(\frac{P}{P_c}\right)^{3.26}} \tag{B50}$$

$$C = \frac{c_{31}\left(\frac{P}{P_c}\right)^{1.5} + c_{32}}{B} - c_{33} \tag{B51}$$

Region IV. - If the (P, T) is not in region III (see eq. (B54)) but $P < 50\ MN/m^2$ and T > 623.15 K, then the following should be used:

$$\left(\frac{T}{T_c}\right) = \sum_{i=0}^{8} a_{4i}k^i + \left(\frac{P}{P_c} - c_{40}\right)\sum_{i=0}^{8} b_{4i}k^i \tag{B52}$$

where

$$k = 100\ \lambda \tag{B53}$$

The solution for λ is iterative. And

$$\left(\frac{P}{P_c}\right) = \sum_{i=0}^{2} e_i \left(\frac{T}{T_c}\right)^i \tag{B54}$$

is the boundary of region III-IV.

Region V. - In region V, tabulated values of thermal conductivity as well as computed values of thermal conductivity at equivalent densities were plotted as per figure 2. The resulting curve gives a good representation of the tabulated values, except along the saturation locus. However, deviations up to 8 percent, and 10 percent near critical, can be expected as listed in the table. These tabulated data and this curve fit do not include the anomalous behavior of thermal conductivity in the near-critical region.

$$k = 1 \qquad \text{for } \frac{\rho}{\rho_c} \leq 2.5 \tag{B55}$$

$$k = 2 \qquad \text{for } \frac{\rho}{\rho_c} > 2.5 \tag{B56}$$

$$\lambda = \lambda_1 + 10^Y \tag{B57}$$

where

$$Y = C_{5k}X^4 + C_{4k}X^3 + C_{3k}X^2 + C_{2k}X + C_{1k} \tag{B58}$$

and

$$X = \log_{10}\left(\frac{\rho}{\rho_c}\right) \tag{B59}$$

The constants used in equation (B58) are as follows:

For $k = 1$,

$$C_{1k} = -0.5786154$$

$$C_{2k} = 1.4574646404$$

$$C_{3k} = 0.17006978$$

$$C_{4k} = 0.1334805$$

$$C_{5k} = 0.032783991$$

For $k = 2$,

$$C_{1k} = -0.70859254$$

$$C_{2k} = 0.94131399$$

$$C_{3k} = 0.064264434$$

$$C_{4k} = 1.85363188$$

$$C_{5k} = 1.98065901$$

The following coefficients are used in the equations for thermal conductivity:

$a_0 = -0.92247$	$b_0 = -0.20954276$
$a_1 = 6.728934102$	$b_1 = 1.320227345$
$a_2 = -10.11230521$	$b_2 = -2.485904388$
$a_3 = 6.996953832$	$b_3 = 1.517081933$
$a_4 = -2.31606251$	$b_{31} = 6.637426916\times10^5$
$a_{31} = 0.01012472978$	$b_{32} = 1.388806409$
$a_{32} = 0.05141900883$	$b_{40} = 1.514476538$
$a_{40} = 1.365350409$	$b_{41} = -19.58487269$
$a_{41} = -4.802941449$	$b_{42} = 113.6782784$

$a_{42} = 23.60292291$

$a_{43} = -51.44066584$

$a_{44} = 38.86072609$

$a_{45} = 33.47617334$

$a_{46} = -101.0369288$

$a_{47} = 101.2258396$

$a_{48} = -45.69066893$

$b_{43} = -327.0035653$

$b_{44} = 397.3645617$

$b_{45} = 96.82365169$

$b_{46} = -703.0682926$

$b_{47} = 542.9942625$

$b_{48} = -85.66878481$

$c_0 = 0.08104183147$

$c_1 = -0.4513858027$

$c_2 = 0.8057261332$

$c_3 = -0.4668315566$

$c_{31} = 3.388557894\times10^5$

$c_{32} = 576.8$

$c_{33} = 0.206$

$c_{40} = 1.017179024$

$d_{31} = 2.100200454\times10^{-6}$

$d_{32} = 23.94$

$d_{33} = 3.458$

$d_{34} = 13.6323539$

$d_{35} = 0.0136$

$d_{36} = 7.8526\times10^{-3}$

$e_1 = 50.60225796$

$e_2 = -105.6677634$

$e_3 = 55.96905687$

Thermal Conductivity - Anomalous Region

The Senger technique (ref. 12) as modified in reference 13 and again herein is calculated for $0.4 \le \rho/\rho_c \le 1.6$. Let

$$X^{\beta} = \left(\frac{\left|1 - \frac{T}{T_c}\right|}{\left|1 - \frac{\rho}{\rho_c}\right|^{1/0.35}}\right)^{0.35}$$

and λ_F represent the nonanomalous or frozen thermal conductivity. For $X^\beta < 0.4$,

$$\lambda - \lambda_F = \frac{11.6\times10^{-5}}{\sqrt{\frac{\rho}{\rho_c}}\left|1 - \frac{\rho}{\rho_c}\right|^{1.71}} \tag{B60}$$

For $X^\beta > 3$,

$$\lambda - \lambda_F = \frac{11.6\times10^{-5}}{\sqrt{\frac{\rho}{\rho_c}}\left|1 - \frac{T}{T_c}\right|^{0.6}} \tag{B61}$$

For $0.4 \leq X^\beta \leq 3$,

$$\lambda - \lambda_F = \frac{11.6\times10^{-5}\ 10^{X_0}}{\sqrt{\frac{\rho}{\rho_c}}\left|1 - \frac{T}{T_c}\right|^{0.6}} \tag{B62}$$

where

$$X_0 = \sum_0^4 a_i \zeta^i \tag{B63}$$

$$\zeta = \log_{10} X^\beta$$

and

$$a_0 = -0.17384732$$

$$a_1 = 0.82350372$$

$$a_2 = -1.55213983$$

$$a_3 = -0.12626138$$

$$a_4 = 2.83922425$$

Surface Tension and the Laplace Constant

Surface tension is given by

$$\sigma = \frac{a_1(T - T_c)^2}{1 - 0.83(T - T_c)} + \sum_{i=2}^{5} a_i(T - T_c)^i \tag{B64}$$

where

$$a_1 = 0.1160936807$$

$$a_2 = 1.121404688\times10^{-3}$$

$$a_3 = 5.75280518\times10^{-6}$$

$$a_4 = 1.28627465\times10^{-8}$$

$$a_5 = 1.149719240\times10^{-11}$$

The Laplace constant is

$$L = \sqrt{\frac{\sigma}{g(\rho_L - \rho_V)}} \tag{B65}$$

where g is the local acceleration. If g is the acceleration of gravity,

$$g = 980.665\ \mathrm{cm/sec}^2 \tag{B66}$$

APPENDIX C

DESCRIPTION OF IMPORTANT SUBROUTINES IN WASP

This appendix includes a discussion of the input/output and important features of the major subroutines in WASP. The method of solution used for the equations is indicated. The equation numbers refer to equations presented in appendix B. The FORTRAN IV variables mentioned correspond to the program listing in appendix E. The shorter subroutines not included in appendix C are completely described by comments in the listing in appendix E. Subroutine WASP has been described in the main text, in tables I and II; hence, the reader is assumed to be familiar with subroutine WASP.

MATHEMATICAL ROUTINES

The mathematical routines are as follows:

(1) Function SOLVE (X1, F, DF): This routine performs a Newton-Raphson iteration given the initial estimate X1, the function F, and the derivative function DF. The convergence is determined when $|(X_N - X_{N-1})/X_N| < \text{TOL}$. The value of TOL is 1. E-5 for iterations 1 to 40, 1. E-4 for 41 to 60, 1. E-3 for 61 to 80, and 1. E-2 for 81 to 100. In all cases studied the convergence was usually obtained in fewer than 40 iterations. For the exceptions, usually in the near-critical region of the PVT surface, the values returned with the increased tolerance are the best obtainable using equation (B3). The maximum number of iterations is 100, and an appropriate message is written if this number is reached.

(2) Subroutines ROOT (X0, X2, FOFX, FUNC, X1) and ROOTX (X0, X2, FOFX, FUNC, X1): These two routines are identical except for name. The duplication is necessary for the double iterations in the solutions for temperature and density given pressure and enthalpy (KS=4) or pressure and entropy (KS=5) as input. (See also table I.)

The solution method is a modified half-interval search technique for a monotonic function, FUNC, with a root between X0 and X2 such that FUNC(X1) = FOFX where X1 is the answer returned. The number of iterations does not exceed 100, and the tolerance is varied in the same manner as in function SOLVE. In addition, both the root and the function value FUNC(X1) must meet a tolerance. While the tolerance on X1 is TOL, the tolerance on FUNC(X1) is 10*TOL. Error messages are written when the iterations reach 100 or when there is no solution in the interval X0 to X2.

Q-FUNCTIONS

These routines use D and TAU in program units of KU=1. Entry points with TAU as input indicate an iteration where D is known, while entry points with D and TAU as input are used in solving for D and in calculating all derived properties.

The Q-functions are as follows:

(1) Function QMUST(D) calculates summation terms involving D needed by other Q-functions and stores them in COMMON/QAUX/ and /QSI/. ENTRY QMUST2(TAU) calculates summation terms involving TAU and stores them in /QAUX/.

(2) Function QCALC(TAU) calculates equation (B4).

(3) Function QTD(TAU) calculates equation (B8).

(4) Function QDTA(TAU) and ENTRY QDT(D, TAU) calculate equation (B9).

(5) Function Q2DTA(TAU) and ENTRY Q2DT(D, TAU) calculate equation (B10).

(6) Function Q2D2TA(TAU) and ENTRY Q2D2T(D, TAU) calculate equation (B11).

(7) Function Q2T2D(TAU) calculates equation (B12).

FUNCTION CHECK

Function CHECK includes

(1) ENTRY TCHECK (KU, KR, T)

(2) ENTRY PCHECK (KU, KR, P)

(3) ENTRY DCHECK (KU, D)

These entry points convert the variables from the user's units to the program's units, represented by KU=1, and check for out-of-range variables. Appropriate messages are written for any out-of-range input, but the calculation is allowed to continue.

The following subroutines use the mathematical routines, the Q-functions, function CHECK, and the subroutines listed with each in table V. The use of these subroutines is determined by the KS and KP options (see table I) and are called by subroutine WASP. If a user wants to use only a few of these subroutines, he can disassemble the WASP program by following the instructions in appendix D and the discussion for the routine of interest. Subroutine WASP uses the temperature parameter TAU (in user's units) for input to the subroutines. All the derived thermodynamic property and transport property subroutines assume that TAU, P, and D have been previously calculated. These subroutines are called twice by WASP for saturation properties, once with DL and once with DV as input for D.

SUBROUTINES TO OBTAIN STATE VARIABLES (KS OPTIONS)

The subroutines used to obtain the state variables are as follows:

(1) Subroutine DENS (KU, TAU, P, D, DL, DV, KR): This routine solves equation (B13) for the density, given TAU and P in units indicated by KU. The region number (KR) is returned, and the density is returned in D for KR=2 or KR=3. For KR=1, the saturation values are returned in DL and DV. If KR=1 for input and either TAU=0 or P=0 for input, the saturated value is calculated and returned for the variable which was input as 0.

The solution is obtained by ROOT for subcritical pressures and by SOLVE for saturation or supercritical pressures. Special initial estimates were found necessary for convergence near subcritical temperatures with SOLVE and for the interval used by ROOT in the region $P > P_c$ and $373.15 \text{ K} < T < 453.15 \text{ K}$ (100° C $< t < 180^{\circ}$ C).

(2) Subroutine PRESS (KU, TAU, D, P, KR): This routine calculates pressure (eq. (B13)) as a function of TAU and D in regions KR=2 and KR=3 and as a function of TAU only in region KR=1 (using subroutine PSSS). The result, P, is returned in user's units indicated by KU. The correct value of KR is also returned and the calculation is direct.

(3) Subroutine TEMP (KU, P, D, TAU, KR): This routine solves equation (B13) for the temperature parameter TAU, given P and D in user's units specified by KU. In regions KR=2 and KR=3, SOLVE is used to obtain the solution. In region KR=1, which is either input or determined, TAU is a function of P only and is obtained from subroutine TSS by solving equation (B31) for TAU. Subroutine TSS also uses SOLVE. The correct KR is returned.

(4) Subroutine TEMPPH (KU, P, H, TAU, D, DL, DV, KR): This routine solves equation (B13) by using equation (B20) for the temperature parameter TAU and density D, given P and H as input in user's units indicated by KU. The double iteration is performed by using ROOT and ROOTX with function TSHF for regions KR=2 and KR=3. In region KR=1, the saturation values are determined for DL and DV by DENS, and TAU is found by function TSS (using SOLVE). KR is also returned.

(5) Subroutine TEMPPS (KU, P, S, TAU, D, DL, DV, KR): This routine solves equations (B13) and (B24) for TAU and D in the same manner as TEMPPH, using P and S as input and function TPSF for the double iteration with ROOT and ROOTX.

SUBROUTINES TO OBTAIN DERIVED THERMODYNAMIC PROPERTIES

The subroutines used to obtain derived thermodynamic properties assume that the variables TAU and D have been input or previously calculated in the user's units. This condition is satisfied in subroutine WASP. When KR=1 is input or has been so deter-

mined, subroutine WASP makes two calls to each routine, once using DL and once DV for input D; and the corresponding saturated variable is output [(HL, SL, etc.), (HV, SV, etc.)].

These subroutines are as follows:

(1) Subroutine ENTH (KU, TAU, D, H): This routine calculates enthalpy H in user's units (KU) by using equation (B20).

(2) Subroutine ENT (KU, TAU, D, S): This routine calculates entropy S in user's units (KU) by using equation (B24).

(3) Subroutine CPPRL (KU, TAU, D, CP, CV, GAMMA, C): This routine calculates the following in user's units indicated by KU:

(a) Specific heat at constant pressure, CP, eq. (B27)

(b) Specific heat at constant volume, CV, eq. (B26)

(c) Specific-heat ratio, GAMMA, eq. (B28)

(d) Sonic velocity, C, eq. (B30)

In addition, the first partial derivatives of P are calculated and returned in COMMON/PARTLS/PTV, PDT in the units of KU=1 only. PTV is equation (B16) and PDT is equation (B14).

SUBROUTINES TO OBTAIN TRANSPORT PROPERTIES

The three routines used to obtain the transport properties assume that the input variables for pressure and density and the temperature parameter τ are all available in user's units. They are called twice by WASP for saturation conditions, once with DL and once with DV as input for density DIN.

(1) Subroutine VISC (KU, KR, TIN, PIN, DIN, SVISC): This routine uses TIN, PIN, and DIN as input in user's units KU. Dynamic viscosity, SVISC, is calculated by using one or more of equations (B32) to (B39), depending on the region of the input variables as shown in figure 1 and explained in appendix B. All calculations of dynamic viscosity are direct evaluations of curve fits.

(2) Subroutine THERM (KU, KR, TIN, PIN, DIN, EXCESK, TCOND): This routine uses TIN, PIN, and DIN in user's units KU to calculate the thermal conductivity TCOND in user's units KU. An optional coding section calculates the critical excess thermal conductivity associated with the critical anomaly in the PVT region, $0.6 < \rho/\rho_c < 1.4$ and $0.9 < T/T_c < 1.1$. See also references 12, 13, and 15 and the subroutine listing in appendix E.

The equations used for thermal conductivity are (B40) to (B59) for the different regions as shown in figure 2. The equation for region IV (eq. (B52)) is iterative. The thermal conductivity for the other regions is calculated by direct evaluation of curve fits.

(3) Subroutine SURF (KU, KR, TIN, SURFT): This routine uses TIN, the input temperature parameter, in user's units, to calculate both the surface tension of liquid water and the Laplace constant. The calculated surface tension is returned in SURFT, and the Laplace constant (ALC) is returned in COMMON/LAPLAC/ALC. The statement COMMON/LAPLAC/ALC must appear in the user's calling routine if the Laplace constant is desired.

APPENDIX D

MODULAR DESIGN OF WASP

A user with limited core storage or with specific property needs may wish to use only parts of WASP. The subroutines have been coded so that most of the subroutines corresponding to the ''KP option'' requests may be removed without causing errors in logic or calculations. Table V indicates which routines are absolutely necessary and which are optional. The conditions for removal must be strictly followed. For simplicity, the KP options are discussed as though only one option was being requested. In reality, the input variable KP is always the summation of the KP option variables. To modify a statement number in subroutine WASP, simply replace it with a continue statement of the same number. For example, to remove the viscosity option, remove subroutine VISC. In subroutine WASP, alteration would read as follows:

```
160 CONTINUE
170 DO175 I=1, 32
```

If the user wishes to omit many options, he should rewrite subroutine WASP for efficiency.

APPENDIX E

PROGRAM LISTING AND FLOW CHART FOR SUBROUTINE WASP

PROGRAM LISTING

```
$IBFTC AQUA
      SUBROUTINE WASP (KS,KP,TT,P,D,H,KR)
C KEYES  KENNAN   HILL   MOORE   EQUATION  OF STATE FOR WATER
C       ------------------------VERSION MARCH 1,1972------------------
C
C         COMPUTE THE STATE RELATIONS AND THERMODYNAMIC AND TRANSPORT
C         PROPERTIES OF WATER  GIVEN TEMPERATURE TT, PRESSURE P,
C         DENSITY D, OR ENTHALPY H, OR ENTROPY S.  STATE RELATIONS ARE
C         SPECIFIED BY KS.  THERMODYNAMIC AND TRANSPORT PROPERTIES
C         ARE SPECIFIED BY KP.  IF KR IS RETURNED OR SPECIFIED AS 1,
C         PROPERTIES ARE COMPUTED AT SATURATION.
C
      COMMON/PROPTY/KU,DL,DV,HL,HV,S,SL,SV,CV,CVL,CVV,CP,CPL,CPV,GAMMA,
     1GAMMAL,GAMMAV,C,CL,CVP,MU,MUL,MUV,K,KL,KV,SIGMA,EXCL,EXCV,EXCESK
      REAL MU,MUL,MUV,K,KL,KV
      COMMON/CHECKS/DCH1,   DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,H
     1SCH1,HSCH2
C

C   TAU IS THE TEMPERATURE PARAMETER USED IN THE EQUATION OF STATE
C          TAU IS EQUIVALENT TO T IN THIS SUBROUTINE
C
C
      DIMENSION KPC1(32), KPC2(32), KPC3(32),KPC4(32)
      DATA KPC1 /2,3,6,7,10,11,14,15,18,19,22,23,26,27,30,31,34,35,38,
     139,42,43,46,47,50,51,54,55,58,59,62,63/
      DATA KPC2 /4,5,6,7,12,13,14,15,20,21,22,23,28,29,30,31,36,37,38,
     139,44,45,46,47,52,53,54,55,60,61,62,63/
      DATA KPC3 /8,9,10,11,12,13,14,15,24,25,26,27,28,29,30,31,40,41,42,
     143,44,45,46,55,56,57,58,59,60,61,62,63/
      DATA KPC4 /16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,
     148,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63/
      T=TT
       IF (TT.GT.0.)  T=1000./TT
      GO TO (10,20,30,40,45),KS
C
C         COMPUTE DENSITY
C
   10 CALL DENS(KU,T,P,D,DL,DV,KR)
      IF ( TT .EQ. 0.0) TT=1000./T
      GO TO 50
C
```

```
C         COMPUTE PRESSURE
C
   20 CALL PRESS(KU,T,D,P,KR)
      GO TO 50
C
C         COMPUTE TEMPERATURE
C
   30 CALL TEMP(KU,P,D,T,KR)
      TT=1000./T
      GO TO 50
C
C         COMPUTE TEMPERATURE AND DENSITY GIVEN PRESSURE AND ENTHALPY
C
   40 CALL TEMPPH(KU,P,H,T,D,DL,DV,KR)
      TT=1000./T
      GO TO 50
   45 CALL TEMPPS ( KU,P,S,T,D,DL,DV,KR )
      TT=1000./T
   50 IF (KR.NE.1.OR.(KS.EQ.1.OR.KS.GT.3)) GO TO 55
C
C  OBTAIN SATURATION DENSITIES DL AND DV FOR KS=2 AND KS=3 CALLS WHEN
C    KR=1
C
      CALL DENS(KU,T,P,D,DL,DV,1)
   55 IF (MOD(KP,2))60,70,60
C
C         COMPUTE ENTHALPY
C
   60 IF (KR.EQ.1) GO TO 65
      CALL ENTH(KU,T,D,H)
      GO TO 70
   65 CALL ENTH(KU,T,DL,HL)
      CALL ENTH (KU,T,DV,HV)
   70 DO 80 I=1,32
      IF (KP-KPC1(I))110,100,80
   80 CONTINUE
      GO TO 110
C
C         COMPUTE ENTROPY
C
  100 IF (KR.EQ.1) GO TO 105
      CALL ENT(KU,T,D,S)
      GO TO 110
  105 CALL ENT (KU,T,DL,SL)
      CALL ENT(KU,T,DV,SV)
  110 DO 120 I=1,32
      IF(KP-KPC2(I)) 140,130,120
  120 CONTINUE
      GO TO 140
C
C         COMPUTE SPECIFIC HEATS AND GAMMA AND SONIC VELOCITY
C
  130 IF (KR.NE.1) GO TO 135
      CALL CPPRL(KU,T,DL,CPL,CVL,GAMMAL,CL)
      CALL CPPRL(KU,T,DV,CPV,CVV,GAMMAV,CVP)
      GO TO 140
  135 CALL CPPRL(KU,T,D,CP,CV,GAMMA,C)
  140 DO 150 I=1,32
      IF (KP-KPC3(I)) 170,160,150
  150 CONTINUE
      GO TO 170
C
```

```
C         COMPUTE VISCOSITY
C
  160 IF (KR.NE.1) GO TO 165
      CALL VISC(KU,KR,T,P,DL,MUL)
      CALL VISC(KU,KR,T,P,DV,MUV)
      GO TO 170
  165 CALL VISC(KU,KR,T,P,D,MU)
  170 DO 175 I=1,32
      IF(KP-KPC4(I)) 190,180,175
  175 CONTINUE
      GO TO 190
C
C         COMPUTE THERMAL CONDUCTIVITY
C
  180 IF (KR.NE.1) GO TO 220
      CALL THERM (KU,KR,P,T,DL,EXCL,KL)
      CALL THERM (KU,KR,P,T,DV,EXCV,KV)
      GO TO 190
  220 CALL THERM (KU,KR,P,T,D,EXCESK,K)
  190 IF(KP-32) 230,240,240
C
C         COMPUTE SURFACE TENSION
C
  240 CALL SURF (KU,KR,T,SIGMA)
  230 RETURN
      END
```

```
$IBFTC BLOC
      BLOCK DATA
C       ----------------------VERSION MARCH 1,1972-----------------
      DIMENSION A1(10),A2(10),A3(10),A4(10),A5(10),A6(10),A7(10)
      EQUIVALENCE (A1(1),A(1,1)),(A2(1),A(1,2)),(A3(1),A(1,3)),(A4(1),A(
     11,4)),(A5(1),A(1,5)),(A6(1),A(1,6)),(A7(1),A(1,7))
      COMMON /CODE/ MESSAG(16)
      COMMON /COF/ A(10,7)
      COMMON /CRIT/ RHOCRT,PCRT,TCRT
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
C
      COMMON/COSAT/CPS1, CPS2,CPS3,CPS4,CPS5,CPS6,CPS7
      COMMON /SICOF/ SIC1,SIC2,SIC3,SIC4,SIC5
      COMMON /CONV1/DCONV(5)
      COMMON /CONV2/TCONV(5)
      COMMON /CONV3/PCONV(5)
      COMMON/CONV4/SCONV(5)
      COMMON/CONV5/CCONV(5)
      COMMON/CONV6/HCONV(5)
      COMMON/CONV7/MCONV(5)
      COMMON/CONV8/KCONV(5)
      COMMON/CONV9/STCONV(5)
      REAL MCONV,KCONV
      DATA A1/29.492937,-132.13917,274.64632,-360.93828,342.18431,
     1 -244.50042, 155.18535, 5.9728487, -410.30848, -416.05860 /
      DATA A2/ -5.1985860, 7.7779182, -33.301902, -16.254622,-177.31074,
     1127.48742, 137.46153, 155.97836, 337.31180, -209.88866   /
      DATA A3/ 6.8335354, -26.149751, 65.326396, -26.181978, 4*0.,
     1-137.46618, -733.96848  /
      DATA A4/ -.1564104, -.72546108, -9.2734289, 4.312584, 4*0.,
     1 6.7874983, 10.401717    /
      DATA A5/ -6.3972405, 26.409282, -47.740374, 56.32313, 4*0.,
     1 136.87317, 645.8188    /
      DATA A6/ -3.9661401, 15.453061, -29.14247, 29.568796, 4*0.,
     1 79.84797, 399.1757     /
      DATA A7/ -.69048554, 2.7407416, -5.102807, 3.9636085, 4*0.,
     1 13.041253, 71.531353  /
      DATA CPS1,CPS2,CPS3,CPS4,CPS5,CPS6,CPS7/
     1      0.29304370E+01,    -0.23095789E+04,     0.34522497E-01,
     2       -.13621289E-03,    0.25878044E-06,     -.24709162E-09,
     3       0.95937646E-13     /
      DATA DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2/0.,1.04539,.000611,22.089,100.,.55555556,1.544912,
     1 3.660900 ,.8,400.,0.,4700.  /
      DATA MESSAG / 96H THERMODYNAMIC AND TRANSPORT PROPERTIES FOR WATER
     1PC=218.07ATM,TC= 647.29 K,ROC=.317 G/CC          /
      DATA RHOCRT,PCRT,TCRT/.317, 22.089, 647.286    /
      DATA SIC1,SIC2,SIC3,SIC4,SIC5/1855.3865, 3.278642,
     1-0.00037903, 46.174, -1.02117 /
      DATA TAUC,RHOA,RHOB,TAUA,E,R/ 1.544912, .634, 1., 2.5, 4.8,.46151/
      DATA TCONV /1.,1.,.55555555 ,2*1.0 /
      DATA PCONV/1.,9.8692327,145.038243,2*1./
      DATA DCONV/2*1.,62.4283,2*1./
      DATA SCONV/2*1.,0.238849,2*1./
      DATA CCONV/2*1.,0.03281,2*1./
      DATA HCONV/2*1.,0.429929,2*1./
      DATA MCONV/2*1.0,.67196899E-1,2*1.0/
      DATA KCONV/2*1.E-2,1.606044E-4,2*1.E-2/
      DATA STCONV/ 2*1.,6.8521766E-5,2*1./
      COMMON/XMINUS/XM1(7)
      DATA XM1/1.,2.,3.,4.,5.,6.,7./
      END
```

```
$IBFTC ROOT1
C      -------------------------VERSION 2/1/72----------------------
       SUBROUTINE ROOTX(X0,X2,FOFX,FUNC,X1)
C
C         SOLVE FOR X1 SUCH THAT FUNC(X1) = FOFX, WHERE X1 LIES
C         BETWEEN X0 AND X2
C
      COMMON /CHECK2/KOUNT
      TOL=1.E-5
      XX0 = X0
      XX2 = X2
      F0 = FUNC(XX0)
      F2 = FUNC(XX2)
      A=(FOFX-F0)/(F2-F0)
      IF (A) 1007,120,120
  120 IF (A-1.) 130,130,1008
  130 IF (FOFX-0.) 80,70,80
   70 ASSIGN 100 TO JUMP
      GO TO 90
   80 ASSIGN 110 TO JUMP
   90 X = (XX0+XX2)/2.
      KOUNT = 0
  150 X1 = X
      KOUNT = KOUNT + 1
      A = FOFX - F2
      FX = FUNC(X)
      FXL=F0+(X-XX0)*(F2-F0)/(XX2-XX0)
      B=ABS((FX-FXL)/(F2-F0))
      IF (A*(FX-FOFX) .LT. 0.) GO TO 1001
      XX0 = X
      F0=FX
      IF (B-.3) 10,20,20
   20 X = (X+XX2)/2.
      GO TO 40
 1001 XX2 = X
      F2 = FX
      IF (B-.3) 10,30,30
   30 X = (XX0+X)/2.
      GO TO 40
   10 X=XX0+(FOFX-F0)*(XX2-XX0)/(F2-F0)
   40 IF (ABS((X-X1)/X)-TOL   ) 50,1000,1000
   50 GO TO JUMP,(100,110)
  100 IF (ABS(FUNC(X))-TOL*10. )60,1000,1000
  110 IF (ABS((FOFX-FUNC(X))/FOFX)-TOL   ) 60,1000,1000
 1000 IF (KOUNT.GT.40) TOL=TOL*10.
      IF (KOUNT.GT.60) TOL=TOL*10.
      IF (KOUNT.GT.80) TOL=TOL*10.
      IF (KOUNT.LT.100) GO TO 150
  160 WRITE (6,170) X1,X
  170 FORMAT (1HL,79HAN ITERATION HAS BEEN TERMINATED AT 100 ITERATIONS.
     1  THE LAST TWO VALUES WERE  ,3G15.5)
   60 X1=X
      RETURN
 1007 X1 = X0
      GO TO 140
 1008 X1 = X2
  140 WRITE(6,141)
  141 FORMAT(1H0,24H SOLUTION OUT OF RANGE
      RETURN
      END
```

```
$IBFTC ROOT2
      SUBROUTINE ROOT (X0,X2,FOFX,FUNC,X1)
C
C     ------------------------VERSION 2/1/72---------------------
C         SAME AS ROOTX - NEEDED  TO  PREVENT  RECURSION
C         SOLVE FOR X1 SUCH THAT FUNC(X1) = FOFX, WHERE X1 LIES
C         BETWEEN X0 AND X2
C
      COMMON /CHECK1/KOUNT
      TOL=1.E-5
      XX0 = X0
      XX2 = X2
      F0 = FUNC(XX0)
      F2 = FUNC(XX2)
      A=(FOFX-F0)/(F2-F0)
      IF (A) 1007,120,120
  120 IF (A-1.) 130,130,1008
  130 IF (FOFX-0.) 80,70,80
   70 ASSIGN 100 TO JUMP
      GO TO 90
   80 ASSIGN 110 TO JUMP
   90 X = (XX0+XX2)/2.
      KOUNT = 0
  150 X1 = X
      KOUNT = KOUNT + 1
      A = FOFX - F2
      FX = FUNC(X)
      FXL=F0+(X-XX0)*(F2-F0)/(XX2-XX0)
      B=ABS((FX-FXL)/(F2-F0))
      IF (A*(FX-FOFX) .LT. 0.) GO TO 1001
      XX0 = X
      F0=FX
      IF (B-.3) 10,20,20
   20 X = (X+XX2)/2.
      GO TO 40
 1001 XX2 = X
      F2 = FX
      IF (B-.3) 10,30,30
   30 X = (XX0+X)/2.
      GO TO 40
   10 X=XX0+(FOFX-F0)*(XX2-XX0)/(F2-F0)
   40 IF (ABS((X-X1)/X)-TOL   ) 50,1000,1000
   50 GO TO JUMP,(100,110)
  100 IF (ABS(FUNC(X))-TOL*10. )60,1000,1000
  110 IF (ABS((FOFX-FUNC(X))/FOFX)-TOL   ) 60,1000,1000
 1000 IF (KOUNT.GT.40) TOL=TOL*10.
      IF (KOUNT.GT.60) TOL=TOL*10.
      IF (KOUNT.GT.80) TOL=TOL*10.
      IF (KOUNT.LT.100) GO TO 150
  160 WRITE (6,170) X1,X
  170 FORMAT (1H1,79HAN ITERATION HAS BEEN TERMINATED AT 100 ITERATIONS.
     1  THE LAST TWO VALUES WERE   ,3G15.5)
   60 X1=X
      RETURN
 1007 X1 = X0
      GO TO 140
 1008 X1 = X2
  140 WRITE(6,141)
  141 FORMAT(1H0,24H SOLUTION OUT OF RANGE          )
      RETURN
      END
```

```
$IBFTC SOLV
C     -------------------------VERSION 2/1/72-----------------------
      FUNCTION SOLVE(XI,F,DF)
C
C        NEWTON-RAPHSON ITERATION GIVEN AN INITIAL ESTIMATE XI
C        AND THE FUNCTIONS F AND DF
      COMMON /CHECK1/NI
      TOL=1.E-5
      NI=0
      XO=XI
      XN=XI
   10 XOO=XO
      XO=XN
      XN=XO-F(XO)/DF(XO)
      NI=NI+1
      IF (ABS((XN-XO)/XN)-TOL   ) 70,20,20
   20 IF (NI.GT.40) TOL=TOL*10.
      IF (NI.GT.60) TOL=TOL*10.
      IF (NI.GT.80) TOL=TOL*10.
      IF (NI-100) 30,50,50
   30 IF (ABS((XN-XOO)/XN)-TOL   ) 40,10,10
   40 XN=(XO+XN)/2.
      GO TO 10
   50 WRITE (6,60) XOO,XO,XN
   60 FORMAT (1HL,81HAN ITERATION HAS BEEN TERMINATED AT 100 ITERATIONS.
     1  THE LAST THREE VALUES WERE   ,3G15.5)
   70 SOLVE=XN
      RETURN
      END
```

```
$IBFTC SCHEC
      FUNCTION   CHECK(KU,KR,T)
C
C        ----------------------VERSION MARCH 1,1972------------------
C
      COMMON/CONV1/DCONV(5)
      COMMON/CONV2/TCONV(5)
      COMMON/CONV3/PCONV(5)
      COMMON/IERROR/ IROUT
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      DIMENSION   FM1(9), FM2(9), FM3(9), FMT(9), ROUT(11)
      DATA  FM1  /51H(1H ,G12.4 ,31HIS OUT OF RANGE FOR T  IN SUB.-,A6 )
     1/
      DATA  FM2  /51H(1H ,G12.4 ,31HIS OUT OF RANGE FOR P  IN SUB.-,A6 )
     1  /
      DATA  FM3  /51H(1H ,G12.4 ,31HIS OUT OF RANGE FOR D  IN SUB.-,A6 )
     1  /
      DATA  ROUT /4HDENS,5HPRESS,4HTEMP ,4HENTH,3HENT ,6HTEMPPH,6HTEMPPS
     1,5HCPPRL,4HVISC,5HTHERM,4HSURF/
C
C        CONVERT TEMPERATURE T TO DEGREES KELVIN AND CHECK
C        FOR OUT OF RANGE.  UNITS ARE SPECIFIED BY KU.  IF KR
C        IS SPECIFIED AS 1, T IS CHECKED FOR OUT OF SATURATION
C        RANGE.
C
      ENTRY   TCHECK (KU,KR,T)
      CHECK=1000.*TCONV(KU)/T
      CH1=1000./TCH3
      CH2=1000./TCH2
      CH3=1000./TCH1
      KODE=1
      DO 1 J=1,9
    1 FMT(J)=FM1(J)
      GO TO 10
C
C         CONVERT PRESSURE TO MN/M**2 AND CHECK
C        FOR OUT OF RANGE.  UNITS ARE SPECIFIED BY KU. IF KR IS
C        SPECIFIED AS 1, P IS CHECKED FOR OUT OF SATURATION
      ENTRY  PCHECK(KU,KR,P)
      CHECK=P/PCONV(KU)
      CH1= PCH1
      CH2= PCH2
      CH3= PCH3
      KODE=0
      DO 2 J=1,9
    2 FMT(J)=FM2(J)
      GO TO 10
C
C         CONVERT DENSITY TO G/CC AND CHECK
C        FOR OUT OF RANGE.  UNITS ARE SPECIFIED BY KU.
C
      ENTRY DCHECK(KU,D)
      CHECK =D/DCONV(KU)
      CH1=DCH1
      CH3=DCH2
      KODE=0
      DO 3 J=1,9
    3 FMT(J)=FM3(J)
      GO TO 20
   10 IF(KR.EQ.1) GO TO 30
```

```
20 IF(CHECK.LT.CH1) GO TO 40
   IF(CHECK.GT.CH3) GO TO 40
25 IF (KODE.EQ.1) CHECK=T/TCONV(KU)
   RETURN
30 IF(CHECK.LT.CH1) GO TO 40
   IF(CHECK.LE.CH2) GO TO 25
40 WRITE(6,FMT) CHECK,ROUT(IROUT)
   GO TO 25
   END
```

```
$IBFTC SUB1
      SUBROUTINE CMUST(D)
C     ----------------------VERSION MARCH 1,1972------------------
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      COMMON /OAUX /  RBDIF(8),RADIF(8),ER,ED,TADIF(7)
      COMMON /COF/ A(10,7)
      COMMON/OS1/SUMI(7)
      RADIF (1)= 1.0
      RADIF (2) = D- RHOA
      RBDIF (1) = 1.0
      RBDIF (2) = D- RHOB
      DO   1    I= 3,8
      RBDIF (I) =  RBDIF (I-1)* RBDIF(2)
    1  RADIF (I)=  RADIF (I-1) *RADIF(2)
      ED =   E*D
      ER=  1.0/ EXP(ED)
      SUMI(1)=0.0
      DO 4 I=1,8
    4 SUMI(1)=SUMI(1)+A(I,1)*RADIF(I)
      SUMI(1)=SUMI(1)+ER*(A(9,1)+A(10,1)*D)
      DO 6 J=2,7
      SUMI(J)=0.0
      DO 5 I=1,8
    5 SUMI(J)=SUMI(J)+A(I,J)*RBDIF(I)
      SUMI(J)=SUMI(J)+ER*(A(9,J)+A(10,J)*D)
    6 CONTINUE
      RETURN
      ENTRY CMUST2(TAU)
      TADIF (1) = 0.0
      TADIF  (2) = 1.0
      TADIF  (3) = TAU-TAUA
      DO    2   I= 4,7
    2  TADIF   (I)= TADIF(I-1)* TADIF(3)
      RETURN
      END
```

```
$IBFTC SUB2
      FUNCTION QCALC(TAU)
C
C        ------------------------VERSION MARCH 1,1972------------------
C--- THE FUNCTION Q(RHO,TAU)
C
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      COMMON /QAUX/ RBDIF(8), RADIF(8),ER,ED, TADIF(7)
      COMMON  /COF / A(10,7)
      COMMON/QS1/SUMI(7)
      TSUM = 0.0
      DO 4 J=2,7
    4 TSUM=TSUM+TADIF(J)*SUMI(J)
      QCALC=SUMI(1)+(TAU-TCH2)*TSUM
      RETURN
      END
```

```
$IBFTC SUB3
      FUNCTION QDTA(TAU)
C        ------------------------VERSION MARCH 1,1972------------------
C
C--- PARTIAL DER OF Q --- PQ/PRHO
      COMMON /QAUX/ RBDIF(8),RADIF(8),ER,ED,TADIF(7)
      COMMON /COF/ A(10,7)
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E,R
      COMMON/XMINUS/XM1(7)
      COMMON/QS2/SUMI(7)
      EQUIVALENCE (SUMI(1),SUM)
    1 TSUM=0.0
      DO 2 J=2,7
    2 TSUM=TSUM+TADIF(J)*SUMI(J)
      QDTA=SUM+(TAU-TAUC)*TSUM
      RETURN
      ENTRY QDT(D,TAU)
      SUM=0.0
      DO 10 I=2,8
   10 SUM=SUM+XM1(I-1)*A(I,1)*RADIF(I-1)
      SUM=SUM+ER*(A(10,1)-E*(A(9,1)+A(10,1)*D))
      DO 15 J=2,7
      SUMI(J)=0.0
      DO 12 I=2,8
   12 SUMI(J)=SUMI(J)+XM1(I-1)*A(I,J)*RBDIF(I-1)
      SUMI(J)=SUMI(J)+ER*(A(10,J)-E*(A(9,J)+A(10,J)*D))
   15 CONTINUE
      GO TO 1
      END
```

```
$IBFTC SUB4
      FUNCTION QTD(TAU)
C       -----------------------VERSION MARCH 1,1972-----------------
C
C--- PARTIAL DER OF Q --- PQ/PTAU
      COMMON /QAUX/RBDIF(8),RADIF(8),ER,ED,TADIF(7)
      COMMON /COF/ A(10,7)
      COMMON /CCNSTS/TAUC,RHOA,RHOB,TAUA,E,R
      COMMON/QS1/SUMI(7)
      COMMON/XMINUS/XM1(7)
      TSUM1 = 0.0
      TSUM2 = 0.0
      DO 18 J=3,7
      TSUM1=TSUM1+XM1(J-2)*TADIF(J-1)*SUMI(J)
   18 TSUM2=TSUM2+TADIF(J)*SUMI(J)
      TSUM2=TSUM2+SUMI(2)
      QTD=TSUM2+(TAU-TAUC)*TSUM1
      RETURN
      END
```

```
$IBFTC SUB5
      FUNCTION Q2T2D(TAU)
C       -----------------------VERSION MARCH 1,1972-----------------
C
C---PARTIAL DER OF Q --- P2Q/PTAU2
      COMMON /QAUX/ RBDIF(8),RADIF(8),ER,ED,TADIF(7)
      COMMON /COF / A(10,7)
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E,R
      COMMON/QS1/SUMI(7)
      COMMON/XMINUS/XM1(7)
      TSUM1 = 0.0
      TSUM2 = 0.0
      DO 2 J=3,7
      TSUM1=TSUM1+XM1(J-2)*TADIF(J-1)*SUMI(J)
      IF (J.EQ.3) GO TO 2
      TSUM2=TSUM2+XM1(J-2)* XM1(J-3)*TADIF(J-2)*SUMI(J)
    2 CONTINUE
      Q2T2D=2.0*TSUM1+(TAU-TAUC)*TSUM2
      RETURN
      END
```

```
$IBFTC SUB6
      FUNCTION Q2DTA(TAU)
C
C        ------------------------VERSION MARCH 1,1972------------------
C--- PARTIAL DER OF Q --- P2Q/PRHO-PTAU
      COMMON /QAUX/  RBDIF(8),RADIF(8),ER,ED,TADIF(7)
      COMMON /COF/ A(10,7)
      COMMON /CONSTS/ TAUC,RHOA,RHCB,TAUA,E ,R
      COMMON/QS3/SUM(6)
      COMMON/XMINUS/XM1(7)
    1 TSUM1=0.0
      TSUM2=0.0
      DO 10 J=3,7
      TSUM1=TSUM1+XM1(J-2)*TADIF(J-1)*SUM(J-1)
   10 TSUM2=TSUM2+TADIF(J)*SUM(J-1)
      TSUM2=TSUM2+SUM(1)
      TSUM1=TSUM1*(TAU-TAUC)
      Q2DTA=TSUM1+TSUM2
      RETURN
      ENTRY Q2DT(D,TAU)
      DO 20 J=2,7
      SUM(J-1)=0.
      DO 15 I=2,8
   15 SUM(J-1)=SUM(J-1)+XM1(I-1)*A(I,J)*RBDIF(I-1)
      SUM(J-1)=SUM(J-1)+ER*(A(10,J)-E*(A(9,J)+A(10,J)*D))
   20 CONTINUE
      GO TO 1
      END
```

```
$IBFTC SUB7
      FUNCTION Q2D2TA(TAU)
C
C        ------------------------VERSION MARCH 1,1972------------------
C--- PARTIAL DER OF Q --- P2Q/PRHO2
      COMMON /QAUX/ RBDIF(8),RADIF(8),ER,ED,TADIF(7)
      COMMON /COF/ A(10,7)
      COMMON /CONSTS/ TAUC, RHOA, RHOB, TAUA, E, R
      COMMON/QS4/SUMI(7)
      COMMON/XMINUS/XM1(7)
    1 TSUM=0.0
      DO 5 J=2,7
    5 TSUM=TSUM+TADIF(J)*SUMI(J)
      Q2D2TA=SUMI(1)+(TAU-TAUC)*TSUM
      RETURN
      ENTRY Q2D2T(D,TAU)
      SUMI(1)=0.0
      DO 3 I=3,8
    3 SUMI(1)=SUMI(1)+XM1(I-1)*XM1(I-2)*A(I,1)*RADIF(I-2)
      SUMI(1)=SUMI(1)+ER*(-E*A(10,1)*(2.0-ED)+E*E*A(9,1))
      DO 10 J=2,7
      SUMI(J)=0.0
      DO 8 I=3,8
    8 SUMI(J)=SUMI(J)+XM1(I-1)*XM1(I-2)*A(I,J)*RBDIF(I-2)
      SUMI(J)=SUMI(J)+ER*(-E* A(10,J)*(2.0-ED)+E*E*A(9,J))
   10 CONTINUE
      GO TO 1
      END
```

$IBFTC SUB8

```
      SUBROUTINE PSSS(PSS)
C       -------------------------VERSION MARCH 1,1972------------------
C
C COMPUTE SATURATION PRESSURE PSSS IN BARS AS A FUNCTION OF T IN DEGREES
C            C AND RETURN ANSWER IN PSS IN MN/M**2
C
      COMMON/COSAT/ CPS1   ,CPS2,CPS3,CPS4,CPS5,CPS6,CPS7
C--- THE T IN THE COMMON BEND17 IS REALLY TAU
      COMMON/TPARAM/T
      DIMENSION   CTIPS(6)
      DATA  CTIPS / .31602383E-03 , 1.00044775, -0.46487771E-05,
     1  0.69431852E-08, 0.15621197E-12 , 1.00043357  /
      TSC = 1000./T -273.15
C---CONVERT  TSC(THERMODYNAMIC CELSIUS  TO INT.PRACTICAL SCALE (C) WHICH
C-----IS USED IN SATURATION  EQUATION
      IF (TSC .GE. 9.996) GO TO 9
      TS = CTIPS(6) * TSC
      GO TO 10
    9 TS =    (((CTIPS(5)*TSC+CTIPS(4))*TSC + CTIPS(3))*TSC +CTIPS(2))
     1        *TSC + CTIPS(1)
   10 TS=TS+273.15
      PSS=10.**(((((CPS7*TS+CPS6)*TS+CPS5)*TS+CPS4)*TS+CPS3)*TS+CPS2/TS+
     1CPS1)
      PSS=PSS/10.0
      RETURN
      END
```

```
$IBFTC SUB9
      FUNCTION TSS(PS)
C        ------------------------VERSION MARCH 1,1972------------------
C
C      COMPUTE SATURATION TEMPERATURE IN DEG C AS A FUNCTION OF PRESSURE
C       IN BARS AND RETURN ANSWER TSS AS TAU IN KELVIN**-1
C
      COMMON/CHECKS/DCH1(1),DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,H
     1SCH1,HSCH2
      COMMON/COSAT/ CPS1   ,CPS2,CPS3,CPS4,CPS5,CPS6,CPS7
      COMMON/BEND9/A1,A2,A3,A4,A5
      DIMENSION  CTT(6)
      DATA CTT /-.30733645E-03, 0.99955209,0.46490458E-05,-.69336443E-08
     1,-0.18086305E-12 , .99956709    /
      EXTERNAL TSSF,DTSSF
      PS1=PS*10.0
      A1=CPS1-ALOG10(PS1)
      A2=5.*CPS7
      A3=4.*CPS6
      A4=3.*CPS5
      A5=2.*CPS4
      TESTM =(1000./TCH2 -20.0 )
      TSS=SOLVE(TESTM,TSSF,DTSSF)
      TSS=TSS-273.15
C---CONVERT THE CALCULATED SATURATION TEMP. FROM INT. PRACTCAL SCALE
C------(C) TO THERMODYNAMIC CELSIUS SCALE
      TSIP=TSS
      IF (TSS .GT. 10.) GO TO 9
      TSS = CTT(6)* TSS
      GO TO 10
    9 TSS =  ((((CTT(5)*TSS + CTT(4))*TSS + CTT(3))*TSS + CTT(2))*TSS +
     1          CTT(1)
   10 TSS = 1000./(TSS+273.15)
      RETURN
      END
```

```
$IBFTC SUB10
      FUNCTION TSSF(TSS)
C        ------------------------VERSION MARCH 1,1972------------------
C
C         FUNCTION USED TO SOLVE FOR SATURATION TEMPERATURE TSS
C         GIVEN PRESSURE
C
      COMMON/COSAT/ CPS1   ,CPS2,CPS3,CPS4,CPS5,CPS6,CPS7
      COMMON/BEND9/A1,A2,A3,A4,A5
      TSSF=(((((CPS7*TSS+CPS6)*TSS+CPS5)*TSS+CPS4)*TSS+CPS3)*TSS+CPS2/
     1TSS+A1
      RETURN
      ENTRY    DTSSF(TSS)
C
C         DERIVATIVE OF FUNCTION USED TO SOLVE FOR SATURATION
C         TEMPERATURE TSS GIVEN PRESSURE
C
       TSSF=((((A2*TSS+A3)*TSS+A4)*TSS+A5)*TSS+CPS3-CPS2/(TSS*TSS)
      RETURN
      END
```

```
$IBFTC PRES1
      SUBROUTINE PRESS(KU,T,D,P,KR)
C        ----------------------VERSION MARCH 1,1972------------------
C
C        COMPUTE PRESSURE P GIVEN TEMPERATURE T AND DENSITY D.
C        UNITS ARE SPECIFIED BY KU.  IF KR IS RETURNED OR
C        SPECIFIED AS 1, P IS COMPUTED AT SATURATION AS A
C        FUNCTION OF T ONLY.
C
      COMMON /CONV3/PCONV(5)
      COMMCN/TPARAM/TS
      COMMON /CCNSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,FSCH2
      COMMON/IERROR/IROUT
      IROUT=2
      TS=TCHECK(KU,KR,T)
C
C        DETERMINE REGION
C
      IF (KR-1) 10,70,10
   10 DS=DCHECK(KU,D)
      IF ( KR .GT. 1) GO TO 80
      IF (TS-TCH2) 50,50,20
   20 CALL DENS(1,TS,ZE,ZE,DSL,DSV,1)
      IF (DS-DSL) 30,60,40
   30 IF (DS-DSV) 50,6C,60
   40 KR=2
      GO TO 80
   50 KR=3
      GO TO 80
C
C        REGION 1
C
   60 KR=1
   70 CALL PSSS(PS)
      GO TO 90
C
C        REGIONS 2 AND 3
C
   8C CALL QMUST(DS)
      CALL QMUST2(TS)
      PS=1000.*R*DS/TS*(1.+DS*(QCALC(TS)+DS*QDT(DS,TS)))
   90 P=PS*PCONV(KU)
      RETURN
      ENC
```

```
$IBFTC DENS1
      SUBROUTINE DENS(KU,T,P,D,DL,DV,KR)
C        ------------------------VERSION MARCH 1,1972------------------
C
C          COMPUTE DENSITY D GIVEN TEMPERATURE T AND PRESSURE P.
C          UNITS ARE SPECIFIED BY KU.  IF KR IS RETURNED OR
C          SPECIFIED AS 1, THE SATURATED LIQUID AND VAPOR DENSITIES,
C          DL AND DV RESPECTIVELY, ARE COMPUTED AS A FUNCTION
C          OF T OR P.  THE OTHER VALUE MUST BE INPUT AS 0.0 .
C
      COMMON /CHECK1/NI
      COMMON /CONV1/DCONV(5)
      COMMON/CONV2/TCONV(5)
      COMMON/CONV3 /PCONV(5)
      COMMON/IERROR/IROUT
      COMMON /CRIT/ RHOCRT,PCRT,TCRT
      COMMON/ PSICON/ SIC1,SIC2,SIC3,SIC4,SIC5
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      COMMON/TPARAM/TS
      COMMON /PRHOT/PS,DS,TT
      EXTERNAL DSF,DDSF
      IROUT=1
      IF (KR.EQ.1) GO TO 70
      TS=TCHECK(KU,KR,T)
      TT = TS
      CALL QMUST2(TS)
      GO TO 5
   70 IF (T.GT.0.0) GO TO 75
      PS=PCHECK(KU,KR,P)
      TS=TSS(PS)
       TT = TS
      IF (T.LE.0.) T=TS *TCONV(KU)
      CALL QMUST2(TS)
      GO TO  5
   75 TS = TCHECK (KU,KR,T)
      TT = TS
      CALL QMUST2(TS)
      CALL PSSS(PS)
      IF (P.LE.0.) P=PS *PCONV(KU)
C
C          DETERMINE REGION
C
    5 IF (KR-1) 10,80,10
   10 PS=PCHECK(KU,KR,P)
      IF (PS-PCH2)110,110,100
  100 IF (TS-TCH2)130,130,120
  120 KR=2
      EST1 = 1.0455
      EST2 = RHOCRT
      TEST = 1000./TS - 273.15
      IF ( TEST .GT. 100.) EST1 = 1.0107054
      IF ( TEST .GT. 180.0) GO TO 121
      IF (TEST.LT.40.) TEST=40.
      EST2=(TEST*(TEST*(TEST*(TEST*.12476711E-09-.52277795E-07)
     1 +.54790571E-05)-.69617325E-03)+1.0220277 )
  121 CALL ROOT (EST1,EST2,0.,DSF,DS)
      GO TO 150
  130 KR=3
      EST=RHOCRT*3.
```

```
      CALL ROOT(EST,DCH1,0.,DSF,DS)
      GO TO 150
  110 IF (TS-TCH2) 50,50,20
   20 CALL PSSS(PSS)
      IF (ABS((PSS-PS)/PSS)-1.E-4) 6(,30,30
   30 IF (PS-PSS) 50,60,40
   40 KR=2
   41 DS=.71854566
      IF ( TS .GT. 1.74474391 DS = .822368
      IF(TS .GT. 1.9487479) DS = .8474576
      IF ( TS .GT. 2.02778051 DS = .907441
      IF ( TS .GT. 2.3C86690) DS=.961538
      IF ( TS .GT. 2.6798874) DS = 1.001001
      IF ( KR .EQ. 1) GO TO 81
      GO TO 90
   50 KR=3
      DS = PS*TS/(1000.*R)
      GO TO 90
C
C         REGICN 1
C
   60 KR=1
   80 CONTINUE
      GO TO 41
   81 CONTINUE
      DSL=SOLVE(DS,DSF,DDSF)
      DS = PS*TS/(1000.*R)
      IF (TCH2/TS.GT..985)DS=.65*RHOCRT
      IF (TCH2/TS.GT..995) DS=.75*RHOCRT
      IF (TCH2/TS.GT..999) DS=.85*RHCCRT
      IF (TCH2/TS.GT..9995) DS=.90*RHOCRT
      DSV=SOLVE(DS,DSF,DDSF)
      DL=DSL*DCONV(KU)
      DV=DSV*DCONV(KU)
      RETURN
C
C         REGIONS 2 AND 3
C
   90 DS=SOLVE(DS,DSF,DDSF)
  150 D=DS*DCONV(KU)
      RETURN
      ENC
```

```
$IBFTC DSFI
      FUNCTION DSF(D )
C
C        FUNCTION USED TO SOLVE FOR DENSITY D  GIVEN TEMPERATURE
C        AND PRESSURE
C
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      COMMON /PRMCT/ PS,DS,TS
      CALL QMUST(D )
      PSTATE=1000.*R*D /TS*(1.+D *(QCALC(TS)+D *QDT(D ,TS)))
      DSF=PSTATE-PS
      RETURN
C
      ENTRY DDSF(D   )
      CALL QMUST(D)
      DDSF=1000.*R/TS*(1.+D*(2.0*QCALC(TS)+4.0*D*QDT(D,TS)+D*D*Q2D2T(D,
     1TS)))
      DSF=DDSF
      RETURN
      END
```

```
$IBFTC TEMP1
      SUBROUTINE TEMP(KU,P,D,T,KR)
C        ------------------------VERSION MARCH 1,1972-------------------
C
C
C   COMPUTE TAU=1000./TEMPERATURE IN USERS UNITS GIVEN PRESSURE AND DEN-
C   SITY. IF KR IS SPECIFIED AS 1 TAU WILL BE A FUNCTION OF PRESSURE ONLY
C
C
      COMMON /CONV2/TCONV(5)
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      COMMON/IERROR/IROUT
      COMMON /PRHOTT/ PS,DS,TS
      EXTERNAL TSF,DTSF
      IROUT=3
      PS=PCHECK(KU,KR,P)
C
C         DETERMINE REGION
C
      IF (KR-1) 10,70,10
   10 DS=DCHECK(KU,D)
      IF (PS-PCH2) 20,20,50
   20 TS=TSS(PS)
      CALL DENS(1,TS,ZE,ZE,DSL,DSV,1)
      IF (DS-DSL) 30,60,40
   30 IF (DS-DSV) 50,60,60
   40 KR=2
      TS = TS+.01
      GO TO 80
   50 KR=3
      TS=1.2
      GO TO 80
C
C         REGION 1
C
   60 KR=1
      GO TO 110
   70 TS=TSS(PS)
      GO TO 110
C
C         REGIONS 2 AND 3
C
   80 CALL QMUST(DS)
      CALL QDT(DS,TS)
      CALL Q2DT(DS,TS)
      TS=SOLVE(TS,TSF,DTSF)
C
C         VERIFY REGION
C
      IF (PS-PCH2)110,110,90
   90 IF (TS-TCH2) 110,100,100
  100 KR=2
  110 T=TS*TCONV(KU)
      RETURN
      END
```

```
$IBFTC TSF1
      FUNCTION TSF(TS)
C       ------------------------VERSION MARCH 1,1972------------------
C
C        FUNCTION USED TO SOLVE FOR TEMPERATURE TS GIVEN PRESSURE
C        AND DENSITY
C
      COMMON /PRHOTT/ PS,D ,T
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      CALL QMUST2(TS)
      PSTATE=1000.*R*D /TS*(1.+D *(QCALC(TS)+D *QDTA(TS)))
      TSF=PSTATE-PS
      RETURN
C
      ENTRY DTSF( TS    )
      CALL QMUST2(TS )
      DTSF=R*D*((1.0+D*D*QDTA  (TS )+D*QCALC(TS ))-TS *D*(D*Q2DTA(TS )
     1+QTD(TS )))
      DTSF=DTSF*(-1000./(TS *TS ))
      TSF=DTSF
      RETURN
      END
```

```
$IBFTC ENTH1
      SUBROUTINE ENTH(KU,TT,D,H)
C       ------------------------VERSION MARCH 1,1972------------------
C
C        THIS ROUTINE COMPUTES ENTHALPY GIVEN THE TEMPERATURE PARAMETER TT
C        AND THE DENSITY D.   I/O UNITS ARE SPECIFIED BY KU.
C     IF SATURATION VALUES ARE NEEDED,THIS ROUTINE MUST BE CALLED TWICE
C        WITH DL AND DV INPUT AS D.
C                ENTHALPY IS RETURNED IN H.
C
      COMMON/IERROR/IROUT
      COMMON/CCNV6/HCONV(5)
      COMMON/SICOF / PSI1,PSI2,PSI3,PSI4,PSI5
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      IROUT=4
      TS=TCHECK(KU,KR,TT)
      DS=DCHECK(KU,D)
      CALL QMUST(DS)
      CALL QMUST2(TS)
      T=1000./TS
       PSI0= (PSI3*T+PSI2)*T+PSI1+(PSI4+PSI5*T)*ALOG(T)
      PSIT=2.*PSI3*T +PSI2+PSI4/T +PSI5*(1.+ALOG(T ))
      H1= PSI0-T*PSIT
      H2=1000.*R/TS*(1.+DS*(QCALC(TS)+TS*QTD(TS)+DS*QDT(DS,TS)))
      H=(H1+H2)*HCONV(KU)
      RETURN
      END
```

```
$IBFTC ENT1
      SUBROUTINE ENT(KU,TT,D,S)
C       ------------------------VERSION MARCH 1,1972------------------
C
C       THIS ROUTINE COMPUTES ENTROPY  GIVEN THE TEMPERATURE PARAMETER TT
C       AND THE DENSITY D.   I/O UNITS ARE SPECIFIED BY KU.
C     IF SATURATION VALUES ARE NEEDED,THIS ROUTINE MUST BE CALLED TWICE
C       WITH DL AND DV INPUT AS D.
C               ENTROPY IS RETURNED IN S.
C
      COMMON/SICOF / PSI1,PSI2,PSI3,PSI4,PSI5
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E ,R
      COMMON/IERROR/IROUT
      COMMON/CCNV4/SCONV(5)
      IROUT=5
      TS=TCHECK(KU,KR,TT)
      DS=DCHECK(KU,D)
      CALL QMUST(DS)
      CALL QMUST2(TS)
      T=1000./TS
      PSIT=2.*PSI3*T +PSI2+PSI4/T +PSI5*(1.+ALOG(T ))
      SSS=-R*(ALOG(DS)+DS*(QCALC(TS)-TS*QTD(TS)))-PSIT
      S=SSS*SCCNV(KU)
      RETURN
      END
```

```
$IBFTC TEMPP1
      SUBROUTINE TEMPPH(KU,P,H,T,D,DL,DV,KR)
C     ------------------------VERSION MARCH 1,1972-------------------
      COMMON /CONV1/DCONV(5)
      COMMON /CONV2/TCONV(5)
      COMMON/CCNV6/HCONV(5)
      COMMON/PHCALL/PS,HS ,SS
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      COMMON/IERROR/IROUT
      EXTERNAL TSHF
      PS=PCHECK(KU,KR,P)
      IROUT=6
      HS=H/HCONV(KU)
      IF (HS-HSCH1) 20,10,10
   10 IF (HS-HSCH2) 40,40,20
C
C         INPUT H - OUT OF RANGE TAG
   20 WRITE(6,301) HS,HSCH1,HSCH2
  301 FORMAT (10HOINPUT H =  ,G14.6, 29HJ/G  IS OUT OF RANGE OF HMIN=
     1 ,F4.1, 10HAND HMAX = ,F7.1,  3HJ/G    )
C
   40 IF (PS-PCH2) 140,140,130
  130 TS1=TCH1
      TS2=TCH3
      GO TO 110
  140 TS=0.0
      CALL DENS(1,TS,PS,ZE,DL,DV,1)
      IF (KR-1) 50,70,50
   50 CALL ENTH(1,TS,DL,HSL)
      CALL ENTH(1,TS,DV,HSV)
      IF (HS-HSL) 90,70,60
   60 IF (HS-HSV) 70,70,100
C
C         REGION 1
C
   70 KR=1
   80 CALL DENS(1,TS,ZE,ZE,DSL,DSV,1)
      DL=DSL*DCONV(KU)
      DV=DSV*DCONV(KU)
      GO TO 120
C
C         REGION 2
C
   90 KR=2
      TS1=TCH3
      PS=PS*1.00011
      TS2=1000./(1000./TS-1.E-5)
      GO TO 110
C
C         REGION 3
C
  100 KR=3
      TS1=1000./(1000./TS+1.E-5)
      PS= PS*.99988
      TS2=TCH1
```

```
C
C         REGICNS 2 AND 3
C
  110 CALL ROOTX(TS1,TS2,HS,TSHF,TS)
      CALL DENS(1,TS,PS,DS,ZE,ZE,KR)
      D=DS*DCCNV(KU)
C
C         VERIFY REGION
C
      IF (PS-PCH2) 120,120,150
  150 IF ( TS-TCH2) 170,170,160
  160 KR=2
      GO TO 120
  170 KR=3
  120 T=TS*TCCNV(KU)
      RETURN
      END
```

```
$IBFTC STEMPS
      SUBROUTINE TEMPPS (KU,P,S,T,D,DL,DV,KR )
C       ------------------------VERSION MARCH 1,1972------------------
      COMMON /CONV1/DCONV(5)
      COMMON/CCNV4/ SCONV(5)
      CCMMON /CONV2/TCONV(5)
      CCMMON/PHCALL/PS,HS ,SS
      COMMON/CHECKS/DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      COMMON/IERROR/IROUT
      EXTERNAL TPSF
      IROUT=7
      SMAX=13.26
      PS=PCHECK(KU,KR,P)
      SS = S/SCONV(KU)
      IF (SS .LT. 0.0) GO TC 20
      IF ( SS.LE.SMAX) GO TO 40
C
C       INPUT S   -   OUT OF RANGE TAG
   20 WRITE(6,301) SS,SMAX
  301 FORMAT (10H0INPUT S = ,G14.6, 47HJ/G-K IS OUT OF RANGE OF  SMIN=0.
     10 AND SMAX=   ,F7.1,5HJ/G-K)
   40 IF (PS-PCH2) 140,140,130
  130 TS1=TCH1
      TS2=TCH3
      GO TO 110
  140 TS=0.0
      CALL DENS(1,TS,PS,ZE,DL,DV,1)
      IF (KR-1) 50,70,50
   50 CALL ENT(1,TS,DL,SSL)
      CALL ENT(1,TS,DV,SSV)
      IF ( SS-SSL )  90,70,60
   60 IF ( SS-SSV) 70,70,100
C
C         REGICN 1
C
   70 KR=1
   80 CALL DENS(1,TS,ZE,ZE,CSL,DSV,1)
      DL=DSL*DCONV(KU)
      DV=DSV*DCONV(KU)
      GO TO 120
C
C         REGICN 2
C
   90 KR=2
      TS1=TCH3
      PS=PS*1.00011
      TS2=TS*1.00001
      GO TO 110
C
C         REGICN 3
C
  100 KR=3
      TS1=TS*.99999
      PS= PS*.99988
      TS2=TCH1
```

```
C
C         REGIONS 2 AND 3
C
  110 CALL ROOTX ( TS1,TS2,SS,TPSF,TS )
      CALL DENS(1,TS,PS,DS,ZE,ZE,KR)
      D=DS*DCONV(KU)
C
C         VERIFY REGION
C
      IF (PS-PCH2) 120,120,150
  150 IF ( TS-TCH2) 170,170,160
  160 KR=2
      GO TO 120
  170 KR=3
  120 T=TS*TCONV(KU)
      RETURN
      END
```

```
$IBFTC TSHF1
      FUNCTION TSHF(TS)
C     ------------------------VERSION MARCH 1,1972------------------
      COMMON/PHCALL/PS,HS ,SS
      KR=0
      CALL DENS(1,TS,PS,DS,ZE,ZE,KR)
      CALL ENTH(1,TS,DS,HSC)
      TSHF=HSC
      RETURN
C
      ENTRY TPSF( TS   )
      KR = 0
      CALL DENS ( 1,TS,PS,DS,ZE ,ZE ,KR )
      CALL ENT(1,TS,DS,SSC)
      TPSF = SSC
      TSHF=TPSF
      RETURN
      END
```

```
$IBFTC CPPRL1
      SUBROUTINE CPPRL(KU,T,D,CP,CV,GAMMA,C)
C       ----------------------VERSION MARCH 1,1972----------------
C
C    THIS SUBROUTINE RETURNS THE FOLLOWING TO WASP IN USERS UNITS.
C         SPECIFIC HEAT AT CONSTANT PRESSURE  =CP
C         SPECIFIC HEAT AT CONSTANT VOLUME    =CV
C         SPECIFIC HEAT RATIO                 =GAMMA
C         SONIC VELOCITY                      = C
C
C       THE PARTIALS PTV AND PDT EXPLAINED BELOW ARE RETURNED IN COMMON.
C
      COMMON/COCPO/     COC1,COC2,COC3
      COMMON/SICOF/  C1,C2,C3,C4,C5
      COMMON /PARTLS/ PTV,PDT
      COMMON/CONSTS/ TAUC,RHOA,RHOB,TAUA,E,R
      COMMON/CONV4/SCONV(5)
      COMMON/CONV5/CCONV(5)
      COMMON/IERROR/IROUT
      IROUT=8
      TS=TCHECK(KU,KR,T)
      TT=1000./TS
      DS= DCHECK(KU,D)
      CALL OMUST(DS)
      CALL OMUST2(TS)
      CQ2T2D=Q2T2D(TS)
      CQCALC=QCALC(TS)
      CQDT=QDT(DS,TS)
      CQTD=QTD(TS)
      CQ2DT=Q2DT(DS,TS)
      CQ2D2T=Q2D2T(DS,TS)
      CV     = -2.*C3*TT+C4/TT-C5-      R*DS*TS*TS*CQ2T2D
C--- PTV IS PARTIAL OF P BY T (NOT TAU)
C--- PDT IS PARTIAL OF P BY RHO
      PTV=R*DS*(1.+DS*(CQCALC+DS*CQDT-TS*(CQTD+DS*CQ2DT)))
      PDT=R*TT*(1.+DS*(2.*CQCALC+DS*(4.*CQDT+DS*CQ2D2T)))
      DHDT=-2.*C3*TT+C4/TT-C5+R*(1.+DS*(CQCALC+DS*CQDT-TS*(DS*CQ2DT+
     1CQTD+TS*CQ2T2D)))
      DHDD=R*(TT*CQCALC+1000.*CQTD+DS*(TT*(3.*CQDT+DS*CQ2D2T)+1000.*
     1CQ2DT))
      CP     = DHDT-DHDD*(PTV/PDT)
      GAMMA=CP/CV
      CP=CP*SCONV(KU)
      CV=CV*SCONV(KU)
      GAMMAP=GAMMA * 10.* PDT
      CS=0.0
      IF ( GAMMAP.GT. 0.0) CS=1000.*SQRT(GAMMAP)
      C= CS*CCONV(KU)
      RETURN
      END
```

```
$IBFTC SRTNSB

      SUBROUTINE SURF(KU,KR,TIN,SURFT)
C       ------------------------VERSION MARCH 1,1972-------------------
C
C     THIS ROUTINE CALCULATES THE SURFACE TENSION OF LIQUID WATER AND
C        THE LAPLACE CONSTANT
C
      COMMON/IERROR/IROUT
      COMMON/CCNV9/STCONV(5)
      COMMON /LAPLAC/ ALC
      DIMENSION A(5)
      DIMENSION X(5)
      DATA (A(I),I=1,5),B,TK /0.11609368  , 1.1214047 E-3, -5.7528052
     1E-6, 1.2862746  E-8, -1.1497193 E-11, 0.83, 647.30  /
C---UNITS OF  G - M/S**2
      DATA   G / 9.80665 /
      IROUT=11
C---T IS DEG K
      TAU=TCHECK(KU,KR,TIN)
      T = 1000./TAU
      SURFT=0.0
      ALC=0.0
      IF (T.GT.TK) RETURN
      X(1)= TK-T
      X(2)= X(1)*X(1)
      X(3)= X(2)*X(1)
      X(4)= X(3)*X(1)
      X(5)= X(4)*X(1)
      Y = (A(1)*X(2))/(1.0+B*X(1))
      DO 1  N=2,5
    1 Y = Y+A(N) * X(N)
      SURFT = Y
C--- UNITS OF SURFT MUST BE DYNE/CM
C--- UNITS OF ALC IS MM.
      TR=  T/647.30
      IF (TR.GT. .998) GO TO 2
      CALL DENS(KU,TAU,ZE,ZE,DL,DV,1)
      ALC  =  SQRT  (SURFT/ (G* ABS (DL-DV)*1000. ) )
C---CONVERSION FACTOR FOR RESULTS TO BE IN MM AS IN THE TABLES
    2 ALC = ALC * 31.622777
      SURFT=SURFT*STCONV(KU)
      RETURN
      END
```

```
$IBFTC DTH
      FUNCTION DTHERM(XLM)
C
C   FUNCTION USED TO SOLVE EQ.(B52) FOR THERMAL CONDUCTIVITY
C
      COMMON/ITERAT/TR,T0,T1,T2,T3,T4,T5,T6,T7,T8
      DOUBLE PRECISION T0,T1,T2,T3,T4,T5,T6,T7,T8
      TCALC=(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*T8+T7)+T6)+T5)+T4)+T3)+
     1T2)+T1)*XLM+T0
      DTHERM=TCALC-TR
      RETURN
      ENTRY DDTH(XLM)
C
C   DERIVATIVE USED TO SOLVE EQ.(B52) IN NEWTON RAPHSON ITERATION
C
      DDTH=(XLM*(XLM*(XLM*(XLM*(XLM*(XLM*8.*T8+7.*T7)+6.*T6)+5.*T5)+
     14.*T4)+3.*T3)+2.*T2)*XLM+T1
      DTHERM=DDTH
      RETURN
      END
```

```
$IBFTC STHCND

      SUBROUTINE THERM(KU,KR,PIN,TIN,DIN,EXCESK,TCOND)
C
C       ----------------------VERSION MARCH 1,1972-----------------
C         SUBROUTINE CALCULATES THE THERMAL CONDUCTIVITY  IN INTERNAL
C         UNITS OF W/CM-K AND CONVERTS TO USERS UNITS
C        EQUATIONS ARE THE INTERNATIONALLY AGREED UPON ONES IN REGIONS
C        WHERE SAME ARE AVAILABLE AND ARE PROPOSED EQUATIONS IN OTHER
C        REGICNS.
C       THE NEAR SUBCRITICAL REGION IS THE AUTHORS FIT
C
      COMMON/CCNV8/KCONV(5)
      COMMON/IERROR/IROUT
      COMMON/ITERAT/TR,T0,T1,T2,T3,T4,T5,T6,T7,T8
      REAL KCCNV
      CCMMON /CRIT/ RHOCRT,PCRT,TCRT
      CCMMON/TPARAM/TAU
      EXTERNAL DTHERM,DDTH
      DIMENSICN CFC(5,2)
      DATA CFC/-.57861540,1.45746404,.17006978,.13348045, .32783991E-1,
     1-.70859254,.94131399,.64264434E-01,1.85363188,1.98065901/
      DOUBLE PRECISION PROP
      DOUBLE PRECISION  A5(5),B5(4),C5(4), T1,SUM1,SUM2,SUM3
      DATA A0,A1,A2,A3,A4/-.17384732,.82350372,-1.55213983,-.12626138,
     1  2.83922425  /
      DATA  A5 / -.9224700000 , 6.728934102 , -10.11230521, 6.996953832,
     1       -2.316062510 / ,  B5 / -.2095427600, 1.320227345,
     2       -2.485904388, 1.517081933  / ,
     3       C5 / .08104183147, -.4513858027 ,.8057261332,-.4668315566 /
      DOUBLE PRECISION  A10(2),B10(2),C10(3),D10(6),A,B,C,T11,T22,T33
      DATA  A10  / .01012472978, .05141900883  /,B10 /663742.6916,
     1 1.388806409 / ,  C10 / 338855.7874, 576.8000000,  .2060000000 /,
     2 D10 / .000002100200454, 23.94090099, 3.458000000,13.63235390 ,
     3       .01360000000, .007852600000  /
      DOUBLE  PRECISION  A8(9),B8(9),C8 ,E9(3),T0,T2,T3,T4,T5,T6,T7,T8
      DATA  A8 / 1.365350409, -4.802941449, 23.60292291, -51.44066584,
     1            38.86072609,  33.47617334,-101.0369288,  101.2258396,
     2            -45.69066893  / ,
     3       B8 / 1.514476538, -19.58487269, 113.6782784, -327.0035653,
     4            397.3645617,  96.82365169,-703.0682926, 542.9942625,
     5          -85.66878481  /  ,  C8 / 1.017179024  /
      DATA  E9 / 50.60225796 , -105.6677634 , 55.96905687  /
      IROUT=10
      PMN=PCHECK(KU,KR,PIN)
      TAU=TCHECK(KU,KR,TIN)
      DS=DCHECK(KU,DIN)
C        CONVERT TAU AND PMN TO VARIOUS UNITS
      TK=1000./TAU
      TR = TK/TCRT
      T = TK-273.15
      PBAR = PMN*10.
      PR=PMN/PCRT
C---CUT OF RANGE CHECK ON PRESS ANC TEMP.
      IF (PBAR.LT. 1.0 .OR. PBAR.GT.500.) WRITE(6,151) TIN,PIN
      IF (T.LT.0.0.OR.T.GT.700.) WRITE(6,151) TIN,PIN
  151 FORMAT (1H0, 5H  T =,F12.4,8H OR   P =,F12.4, 64HIS OUT OF RANGE,
     1RETURNED THERMAL CONDUCTIVITY IS EXTRAPOLATED      )
C
C        CHECK FOR REGION I
C
      IF (T.LE.350..AND.DS.GT.RHOCRT)  GO TO 100
C
```

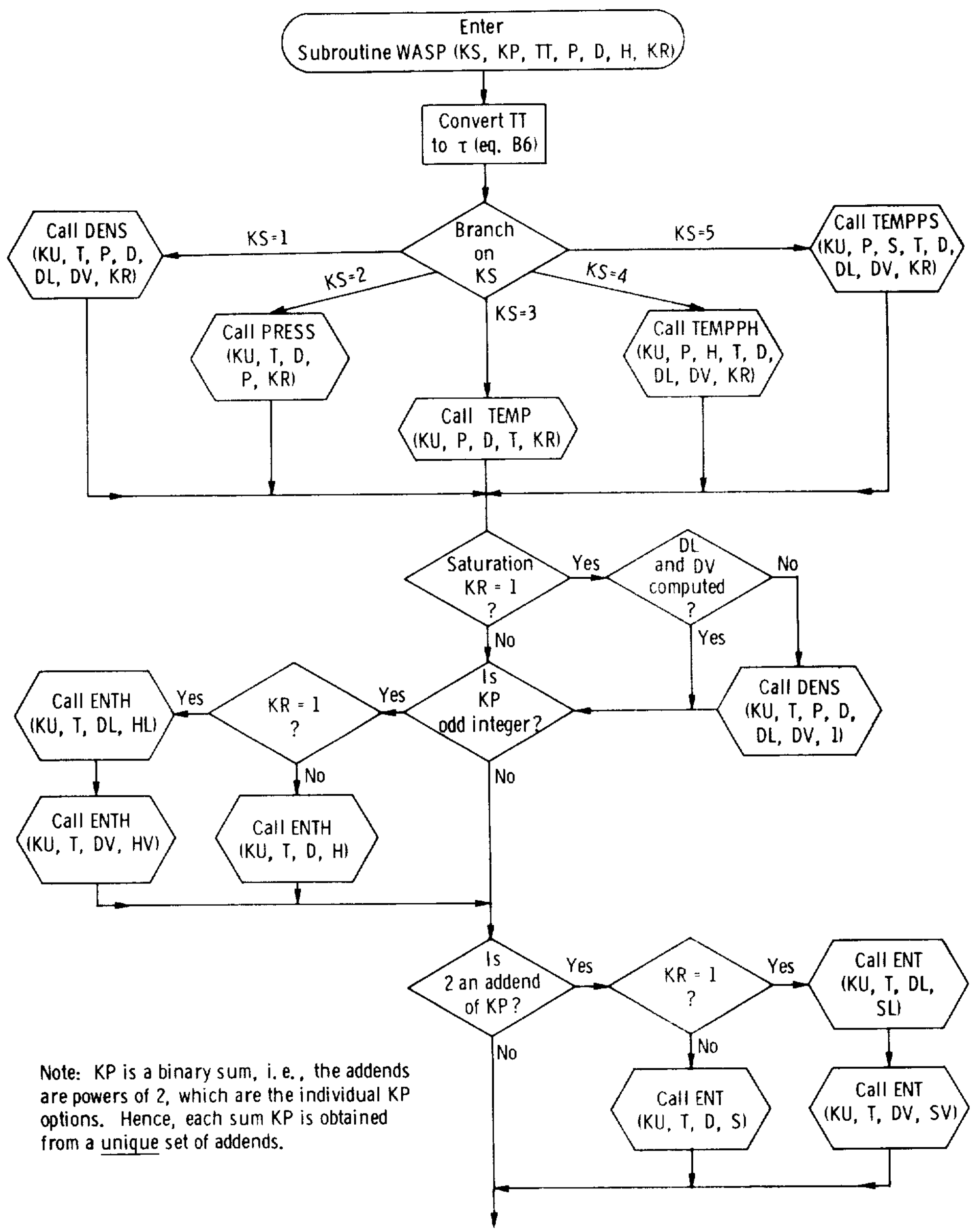
```
C      CHECK FOR JAGGED LOWER BOUNDARY OF REGION IIIOR UPPER PART
C        OF REGION II
C
      IF (PBAR.GT.450..AND.T.LT.550.) GO TO 80
      IF (PBAR.GT.350..AND.T.LT.500.) GO TO 80
      IF (PBAR.GT.275..AND.T.LT.450.) GO TO 80
      IF (PBAR.GT.225..AND.T.LT.425.) GO TO 80
      IF (PBAR.GT.175..AND.T.LT.400.) GO TO 80
C
C      EQUATION (B40) FOR P=1.0 BARS
C
   10 V1 = (17.6 +.0587*T+.000104*T*T -4.51E-08*T*T*T)/1000.
      IF (PBAR.GT.1.000) GO TO 20
      TCOND=V1*KCONV(KU)
      GO TO 500
C
C      EQUATION (B46) FOR REGION II.
   20 ANS=((103.51+.4198*T-2.771E-05*T*T)*DS+2.14821E+14/(T**4.2)*DS*DS
     1)/1000.+V1
      TCOND=ANS*KCONV(KU)
      GO TO 500
C
C                 REGION I CALCULATIONS
C
  100 CALL PSSS(PS)
      PREDD = (PMN-PS)/PCRT
      SUM1=(((A5(5)*TR+A5(4))*TR+A5(3))*TR+A5(2))*TR+A5(1)
      SUM2=((B5(4)*TR+B5(3))*TR+B5(2))*TR+B5(1)
      SUM3=((C5(4)*TR+C5(3))*TR+C5(2))*TR+C5(1)
      TCOND=(SUM1 +   (SUM3*PREDD + SUM2)*PREDD   )*KCONV(KU)
      GO TO 500
C
C      CHECK FOR REGION III-USING BOUNDARY EQUATION (B54) WHICH DIVIDES
C        REGIONS III AND IV.
C    THEN SEPARATE HATCHED REGION WHERE NO EQUATION EXISTS FROM REMAINDER
C        OF REGION IV
   80 IEQUA=10
      IF(T.GT.450.) GO TO 300
      PBOUND=E9(1)+E9(2)*TR+E9(3)*TR*TR
      IF (PR.LT.PBOUND) GO TO 300
      IF(TK.LT.TCRT.AND.DS.LT.RHOCRT) GO TO 400
      IEQUA=8
C
C                 EQUATION (B52) IS SOLVED BY ITERATION
C
  200 NTR=0
      PRDP=PR
      CON=PRDP-C8
      T0 =    A8(1)+ CON*B8(1)
      T1  =   A8(2)+ CON*B8(2)
      T2 =    A8(3)+ CON*B8(3)
      T3 =    A8(4)+ CON*B8(4)
      T4 =    A8(5)+ CON*B8(5)
      T5 =    A8(6)+ CON*B8(6)
      T6 =    A8(7)+ CON*B8(7)
      T7 =    A8(8)+ CON*B8(8)
      T8 =    A8(9)+ CON*B8(9)
C     USE CONDUCTIVITY BASEC ON BOUNDARY AS INITIAL ESTIMATE
      PPR = PR
      PR=PBOUND
      GO TO 300
```

```
  210 PR=PPR
      XHI=.55
      X=(ANS*3.+XHI*2.)/5.
      IF(PR.LE.1.05.AND.TR.LE.1.05) X=ANS+.005
      TCOND=SOLVE(X,DTHERM,CDTH)*KCONV(KU)
C
C      THIS EQUATION DOES NCT ALWAYS CONVERGE NEAR THE BOUNDARY WHERE
C        IT SHOULD. SWITCH TO AUTHORS EXTRAPOLATION IF THIS HAPPENS.
C
      IF (TCCND.LE.0.0) GO TO 400
      GO TO 500
  300 DCN=1.0D+0
      B=(B10(1) *PR**1.63) / (DON+B10(2) *PR**3.26)
      C= (C10(1) *PR**1.5 + C10(2)) / B - C10(3)
      CSP=C
      TEST = DCN-B*D10(1)/TR**7
      T11=(A10(1)*PR+A10(2))*TR**1.445/TEST**CSP
      T22= D10(2)*PR**4 *EXP(-9.0*D10(3)*(TR-1.0))/(DON+D10(4)
     1          /PR**12)
      T33= D10(5) - D10(6) *PR *EXP(-D10(3) * (TR-1.0))
      ANS = T11 + T22*T33
      IF (IEQUA.EQ.8) GO TO 210
      TCOND=ANS*KCONV(KU)
      GO TO 500
C      HATCHED REGION WHERE NO EQUATION EXISTS IN THE REFERENCES.
C           AUTHORS OWN EQ USED HERE WITH 1 BAR EQ.
  400 V1 = (17.6 +.0587*T+.000104*T*T -4.51E-08*T*T*T)/1000.
      XX= ALOG10(DS/RHOCRT)
      KJ=1
      IF (XX.GT.-.39794) KJ=2
      Y=CFC(1,KJ)+(((CFC(5,KJ)*XX+CFC(4,KJ))*XX+CFC(3,KJ))*XX
     1 +CFC(2,KJ))*XX
      TCOND=(10.**Y+V1)*KCONV(KU)
  500 CCNTINUE
C
C      REACTING CCNDUCTIVITY IN THE NEAR CRITICAL REGION BY SENGERS
C
      DRHCC = ABS ( DS - RHOCRT ) / RHOCRT
      DELAMB=0.
      IF( DRHOC.GT. .6) GO TO 520
      DELTC = ABS (TR-1.)
      RAT= DS/RHCCRT
      IF (DRHOC.LT.1.E-4) GC TO 510
      IF (DELTC.LT.1.E-7) GO TO 502
      XBETA = DELTC**.35/DRHOC
      IF (XBETA.GT..4) GO TO 506
  502 DELAMB= 11.6E-5 / (SQRT(RAT)*DRHOC**1.71)
      GC TO 520
  506 IF (XBETA.GT.3.) GO TC 510
      XB= ALOG10(XBETA)
      ARAT= (((A4*XB+A3)*XB+A2)*XB+A1)*XB+A0
      DELAMB=11.6E-5/(SQRT(RAT)*DELTC**.6)*10.**ARAT
      GC TO 520
  510 IF (DELTC.LT.1.E-7) GO TO 525
      DELAMB = 11.6E-5/(SQRT(RAT)*DELTC**.6)
  520 EXCESK= DELAMB
      RETURN
  525 EXCESK =1.E30
      RETURN
      END
```

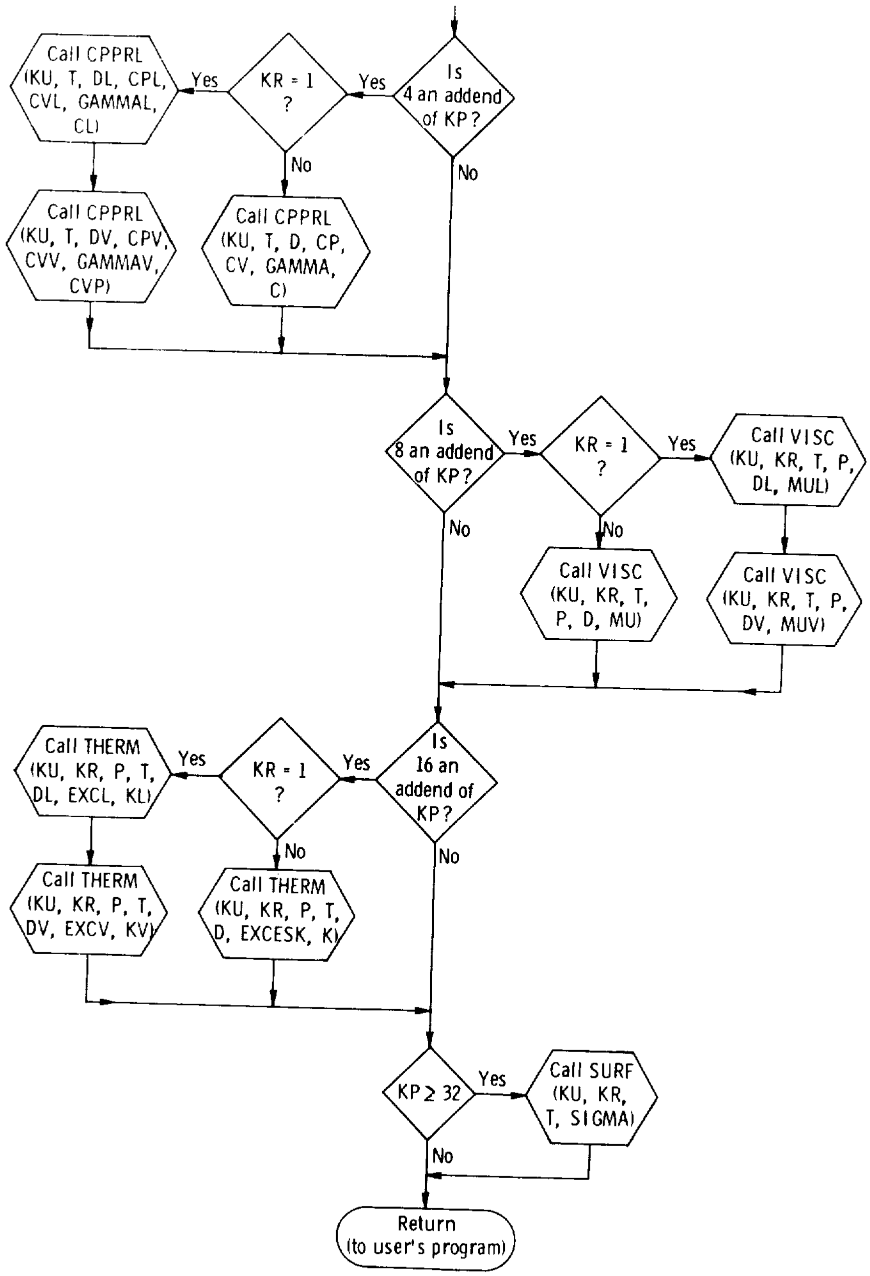
```
$IBFTC DYVISC
      SUBROUTINE VISC(KU,KR,TIN,PIN,DIN,SVISC)
C        ------------------------VERSION MARCH 1,1972-----------------
C
C       CALCULATE THE VISCOSITY GIVEN TAU,P,AND D IN USER-S UNITS KU.
C                   ANSWER RETURNED IN USER-UNITS IN SVISC.
C
      COMMON/IERROR/IROUT
      COMMON/CRIT/ RHOCRT,PCRT,TCRT
      COMMON /TPARAM/ TIN
      COMMON/CONV7/MCONV(5)
      REAL MCONV
      DIMENSION A(5),B(3),C(3),D(3),COF(5,2)
      DATA (A(I),I=1,5) /241.4000,0.38282095,0.21628302,0.1498694,
     1                   0.47118801    /                 ,
     2            (B(I),I=1,3)  /263.4511,0.4219836,80.4000  /       ,
     3          (C(I),I=1,3) / 586.11987, 1204.75394, 0.4219836  /,
     4         (D(I),I=1,3) / 111.35647, 67.320801,3.2051470   /
      DATA COF/-6.4556581,1.3949436,.30259083,.10960682,.15230031E-01,
     1-6.4608381 ,1.61633210,1.C7C97705,-13.938,30.119832  /
      IROUT=9
C---
C---TK IS DEG K. T IS DEG C. TR IS REDUCED TEMP
      TK=1000./TCHECK(KU,KR,TIN)
      T = TK- 273.15
      TR=TK/TCRT
C---P IS BARS.  PMN IS MEGA NEWTONS/M*M ,PR IS REDUCED PRESSURE
      PMN=PCHECK(KU,KR ,PIN)
      P = 10.0*PMN
      PR=PMN/PCRT
C---  DD IS G/CC. SPVR IS REDUCED SPECIFIC VOLUME.
      DD=DCHECK(KU,DIN)
      SPVR= RHOCRT/DD
C
C    CHECK FOR OUT OF RANGE ON P AND T
C
      IF ( P .LT. .99 .OR. P .GT. 800.01)  WRITE(6,101) T,P
      IF ( T .GT. 800.0 .OR. T .LT. 0.0 )   WRITE(6,101)   T,P
  101 FORMAT(1H ,48H OUT OF RANGE. ANSWER IS EXTRAPOLATED  FOR T=
     1,F12.4, 4H P= ,F12.4)
      IF (DD.GT.RHOCRT.AND.T.LT.300.) GO TO 100
      GO TO 110
C
C                      REGION I
C---FOR TEMP-- 0 TO 300 CENT AND PRES--PSAT TO 800 BAR
C
  100 X1 = 10.0 **(A(2)/(TR-A(3))      )
      CALL PSSS(PSS)
      PSR=PSS/PCRT
      X2 = 1.0 + ( PR-PSR)*A(4)*(TR-A(5)   )
      SVISC = (A(1) *X1 *X2 )/10.0**6 *MCONV(KU)
      RETURN
C
C     CALCULATE VISCOSITY FOR 1.0 BAR NEEDED FOR REGIONS II,III,IV
C
  110 VISC1=(B(1)*(TR-B(2))+B(3))
      IF (P.LE.1.0) GO TO 1000
C
C     CHECK FOR TEMPERATURE RANGE WHERE NO CURVE EXISTS
C
      IF (T.GE.300..AND.T.LT.374.15) GO TO 400
      IF (DD.LT.RHOCRT.AND.T.LT.300.) GO TO 200
      GO TO 300
```

```
C
C                    REGION II
C--- FOR PRES-- 1 TO PSAT BAR AND 100 TO 300 CENT
C
  200 SVISC = (VISC1 - 1.0/SPVR*(C(1)-C(2)*(TR-C(3))))/10.**6*MCONV(KU)
      RETURN
C
C                   REGION III
C---FOR PRES -- 1 TO 800 BAR AND 375 TO 800 CENT
C
  300 SVISC =(VISC1 + D(1)/SPVR +D(2)/(SPVR*SPVR) + D(3)/(SPVR*SPVR*SPVR
     1 )   )/10.0**6 *MCONV(KU)
      RETURN
C
C    AUTHORS EXTRAPOLATION USED FOR REGION IV
C
  400 X=ALOG10(1./SPVR)
      KJ=1
      IF (X.GT.-.12493873) KJ=2
      Y= X*(X*(X*(X*COF(5,KJ)+COF(4,KJ))+COF(3,KJ))+COF(2,KJ))+COF(1,KJ)
      SVISC=(VISC1/1.E6+10.**(Y+1.)/.0192)*MCONV(KU)
      RETURN
 1000 SVISC=VISC1/10.**6*MCONV(KU)
      RETURN
      END
```

FLOW CHART FOR SUBROUTINE WASP



Note: KP is a binary sum, i.e., the addends are powers of 2, which are the individual KP options. Hence, each sum KP is obtained from a unique set of addends.


Is 4 an addend of KP?
Yes
No
KR = 1 ?
Yes
No
Call CPPRL (KU, T, DL, CPL, CVL, GAMMAL, CL)
Call CPPRL (KU, T, DV, CPV, CVV, GAMMAV, CVP)
Call CPPRL (KU, T, D, CP, CV, GAMMA, C)
Is 8 an addend of KP?
Yes
No
KR = 1 ?
Yes
No
Call VISC (KU, KR, T, P, DL, MUL)
Call VISC (KU, KR, T, P, DV, MUV)
Call VISC (KU, KR, T, P, D, MU)
Is 16 an addend of KP?
Yes
No
KR = 1 ?
Yes
No
Call THERM (KU, KR, P, T, DL, EXCL, KL)
Call THERM (KU, KR, P, T, DV, EXCV, KV)
Call THERM (KU, KR, P, T, D, EXCESK, K)
KP ≥ 32
Yes
No
Call SURF (KU, KR, T, SIGMA)
Return (to user's program)

APPENDIX F

TEST PROGRAM WITH OUTPUT

The following tables have been generated by WASP to facilitate comparing results to the ASME Tables (ref. 1) and the International Skeleton Tables (refs. 1 and 2). No attempt was made to reproduce the entire reference tables; only a select number of points were chosen at even intervals representative of the total range. The values in the following tables are in the same units and similar form as the reference tables. Results of comparisons between the calculated and the tabulated values are discussed in the main part of the text.

```
$IBFTC MTWASP
      COMMON/PROPTY/KU,DL,DV,HL,HV,S,SL,SV,CV,CVL,CVV,CP,CPL,CPV,GAMMA,
     1GAMMAL,GAMMAV,C,CL,CVP,MU,MUL,MUV,K,KL,KV,SIGMA,EXCL,EXCV,EXCESK
      DIMENSION PSIA(12),TF(11),VOL(12,11),HOUT(12,11),SOUT(12,11)
      DIMENSION PBARTC(13),TCOUT(20,13),TCOUT2(31,13)
      REAL MU,MUL,MUV,K,KL,KV
      DIMENSION T(200),P(200),VL(200),HVOUT(200),SVOUT(200),HLOUT(200)
     1,SLOUT(200),VV(200)
      DIMENSION PNEAR(12),TNEAR(6)
      COMMON/LAPLAC/ALC
      DIMENSION PCP(12),TCP(5),CPARY(12,5)
      DIMENSION PBAR(7),TCENT(20),VOUT(20,7),PSVS(15),TFVS(31),VOUT2(31,
     115)
C
C       MASTER TEST PROGRAM FOR WATER AND STEAM PROPERTY PACKAGE
C
C       PART 1
C
C     COMPARE SATURATION PROPERTIES OF ASME STEAM TABLES  PAGES 83-88
C       AS A FUNCTION OF TEMPERATURE  35-705F IN INCREMENTS OF 10F
C
      KU=3
      NPT=1
      T1=494.
   10 KR=1
      P1=0.0
      CALL WASP(1,3,T1,P1,RHO,H,KR)
      T(NPT)=T1-460.
      P(NPT)=P1
      VL(NPT)=1./DL
      VV(NPT)=1./DV
      SLOUT(NPT)=SL
      SVOUT(NPT)=SV
      HLOUT(NPT)=HL
      HVOUT(NPT)=HV
```

```
      NPT=NPT+1
      T1=T1+12.0
      IF (T1.LE.1165.) GO TC 10
      NPT=NPT-1
C
C       PRINT SATURATICN RESULTS
      WRITE(6,1)
    1 FORMAT(1H1,51H COMPARABLE TO ASME TABLE NO. 1 PAGES 83-88          )
      WRITE(6,2)
      NLIN=0
      DO 20 J=1,NPT
      JJ=NPT-J+1
      NLIN=NLIN+1
      WRITE(6,3) T(JJ),P(JJ),VL(JJ),VV(JJ),HLOUT(JJ),HVOUT(JJ),SLOUT(JJ)
     1,SVOUT(JJ)
      IF (NLIN.LT.50) GO TO 20
      NLIN=0
      WRITE(6,1)
      WRITE(6,2)
    2 FORMAT(1H0,90H  T-F    P-PSIA    VL     FT3/LBM     VV      HL     BTU/L
     1BM    HV          SL   BTU/LBM-R    SV                )
    3 FORMAT(1H F5.0,F10.4,2F12.6,2F12.3,2F12.4)
   20 CONTINUE
      WRITE(6,21)
   21 FORMAT(1H1)
C
C     PART 2    ASME TABLE NO. 3  PAGES 97-203
C
C     PROPERTIES OF SUPERHEATED STEAM AND COMPRESSED WATER
C          TABLE IS 2 PAGES  32-750F AND 750-1500F
C          FOR EACH SET OF ISOBARS
C      WILL COMPARE 12 ISOBARS FOR VARIOUS TEMPERATURES
C
      DATA PSIA/1.0,5.0,25.,100.,200.,500.,1000.,1500.,2000.,5000.,10000
     1.,14500./
      DATA TF/32.,50.,100.,150.,300.,500.,700.,900.,1100.,1300.,1500./
      DO 50 I=1,11
      TIN=TF(I)+460.
      DO 45 J=1,12
      KR=0
      KU=3
      CALL WASP(1,3,TIN,PSIA(J),D,H,KR)
      IF (KR.EQ.1) GO TO 45
      VOL(J,I)=1./D
      HOUT(J,I)=H
      SOUT(J,I)=S
   45 CONTINUE
   50 CONTINUE
      WRITE(6,41 )
      WRITE(6,42)
      DO 60 J=1,12,3
      WRITE(6,44) PSIA(J),PSIA(J+1),PSIA(J+2)
      DO 60 I=1,11
      WRITE(6,43) TF(I),VOL(J,I),HOUT(J,I),SOUT(J,I),VOL(J+1,I),HOUT(J+1
     1,I),SOUT(J+1,I),VOL(J+2,I),HOUT(J+2,I),SOUT(J+2,I)
   41 FORMAT(1H1,20X,36H  COMPARISCN POINTS FOE TABLE NO.3          )
   42 FORMAT(1H0,20X,47H (VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED )
   43 FORMAT(1H ,F6.0,3(F12.5,F11.2,F10.4,5X))
   44 FORMAT(1H0,6X,3(F10.0,4HPSIA,20X))
   60 CONTINUE
C
C     PART 3  ASME TABLE NC. 4  PAGES 208-220
C
C     PRCPERTIES OF SUPERHEATED STEAM AND COMPRESSED WATER IN
C     THE CRITICAL REGION
C
      DATA PNEAR/2860.,3000.,3060.,3100.,3160.,3200.,3260.,3400.,3500.,
     13600.,3800.,3960./
```

```
      DATA TNEAR/650.,680.,710.,740.,770.,800./
      DO 80 I=1,6
      TIN=TNEAR(I)+460.
      DO 70 J=1,12
      KR=0
      CALL WASP(1,3,TIN,PNEAR(J),D,H,KR)
      VOL(J,I)=1./D
      IF (KR.EQ.1) GO TO 70
      HOUT(J,I)=H
      SOUT(J,I)=S
   70 CONTINUE
   80 CONTINUE
      WRITE(6,81)
   81 FORMAT(1H1,20X,40H COMPARISON POINTS FOR ASME TABLE NO. 4           )
      DO 90 J=1,12,3
      WRITE(6,82)
   82 FORMAT(1H0,20X,47H (VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED )
      WRITE(6,44) PNEAR(J),PNEAR(J+1),PNEAR(J+2)
      DO 90 I=1,6
      WRITE(6,43) TNEAR(I),VOL(J,I),HOUT(J,I),SOUT(J,I),VOL(J+1,I),HOUT(
     1J+1,I),SOUT(J+1,I),VOL(J+2,I),HOUT(J+2,I),SOUT(J+2,I)
   90 CONTINUE
C
C       PART 4  ASME TABLE NO. 9 PAGES  278-279
      DATA PCP/1.,4.,10.,30.,60.,100.,200.,400.,1000.,3000.,6000.,10000
     1./
      DATA TCP/32.,300.,700.,1100.,1500./
  109 FORMAT(1H1,20X,42H COMPARISON POINTS FOR ASME TABLE NO. 9        )
      WRITE(6,109)
  111 FORMAT(1H/,4HPSIA,12(4X,F6.0)/1H0,4HTEMP/,3H  F  /)
      WRITE(6,111) PCP
      DO 120 I=1,5
      TIN=TCP(I)+460.
      DO 110 J=1,12
      KR=0
      CALL WASP(1,4,TIN,PCP(J),D,H,KR)
      CPARY(J,I)=CP
  110 CONTINUE
      WRITE(6,112) TCP(I),(CPARY(J,I),J=1,12)
  120 CONTINUE
  112 FORMAT(1H0,F5.0,12F10.3)
C
C            PART 5  VISCOSITY CHECKOUT
C
      DATA PBAR/1.,50.,200.,350.,500.,650.,800./
      DATA TCENT/10.,50.,100.,120.,140.,160.,180.,200.,220.,240.,260.,
     1280.,300.,320.,340.,360.,400.,500.,600.,700./
      DATA PSVS/1.,2.,5.,10.,20.,50.,100.,200.,500.,1000.,2000.,5000.,
     17500.,10000.,12000./
      DATA TFVS/1500.,1450.,1400.,1350.,1300.,1250.,1200.,1150.,1100.,
     11050.,1000.,950.,900.,850.,800.,750.,700.,650.,600.,550.,500.,
     2450.,400.,350.,300.,250.,200.,150.,100.,50.,32./
      WRITE(6,500)
      KL=1
      DO 300 J=1,7
      PIN=PBAR(J)/10.
      DO 300 I=1,20
      TIN=TCENT(I)+273.15
      KR=0
      CALL WASP(1,8,TIN,PIN,D,H,KR)
      IF (KR.EQ.1) GO TO 300
      VOUT(I,J)=MU*1.E5
  300 CONTINUE
      WRITE(6,301)
      WRITE(6,302) PBAR
      DO 320 I=1,20
  320 WRITE(6,303) TCENT(I),(VOUT(I,J),J=1,7)
  301 FORMAT(1H1,42H VISCOSITY TABLE-INTERNATIONAL BOOK               )
```

```
  302 FORMAT(1H0,7(8X,F6.0,4HBARS ))
  303 FORMAT(1H0,F5.0,7(F12.2,6X))
      WRITE(6,500)
      KU=3
      DO 350 J=1,15
      PIN=PSVS(J)
      DO 350 I=1,31
      TIN=TFVS(I)+460.0
      KR=0
      CALL WASP(1,8,TIN,PIN,D,H,KR)
      IF (KR.EQ.1) GO TO 350
C           THIS CONVERSION GETS FROM UINTS=3 OF PROGRAM TO UNITS OF TABL
      VOUT2(I,J)=MU*1.E6*1.4881639/4.7880258
  350 CONTINUE
      WRITE(6,351)
      WRITE(6,352) PSVS
      DO 355 I=1,31
      WRITE(6,353) TFVS(I),(VOUT2(I,J),J=1,15)
  355 CONTINUE
  351 FORMAT(1H1,45H VISCOSITY-ASME TABLE NO. 10 PAGE 280                )
  352 FORMAT(1H0,5H PSIA,2X,15F8.0,/,5H0 T-F  )
  353 FORMAT(1H ,2X,F6.0,15F8.2)
C
C      PART 6   THERMAL CONDUCTIVITY CHECKOUT
C
  360 CONTINUE
      DATA PBARTC/1.,10.,25.,50.,100.,150.,200.,250.,300.,350.,400.,450.
     1,500./
      WRITE(6,500)
      KU=1
      DO 400 J=1,13
      PIN=PBARTC(J)/10.
      DO 400 I=1,20
      TIN=TCENT(I)+273.15
      KR=0
      CALL WASP(1,16,TIN,PIN,D,H,KR)
      IF (KR.EQ.1) GO TO 400
      TCOUT(I,J)=K*1.E4
  400 CONTINUE
      WRITE(6,401)
      WRITE(6,402) PBARTC
      DO 420 I=1,20
  420 WRITE(6,403) TCENT(I),(TCOUT(I,J),J=1,13)
  401 FORMAT(1H1,46H THERMAL CONDUCTIVITY - INTERNATIONAL BOOK          )
  402 FORMAT(1H0,6HP-BARS,13(2X,F7.0)/1H0,3HT-F)
  403 FORMAT(1H0,F5.0,13F9.2)
      WRITE(6,500)
      KU=3
      DO 450 J=1,13
      PIN = PSVS(J)
      DO 450 I=1,31
      TIN = TFVS(I)+460.0
      KR=0
      CALL  WASP (1,16,TIN,PIN,D,H,KR)
      IF(KR.EQ.1) GO TO 450
      TCOUT2(I,J) = K * 1.E3 * 3600.
  450 CONTINUE
      WRITE(6,451)
      WRITE(6,352)(PSVS(I),I=1,13)
      DO 455 I=1,31
  455 WRITE(6,353)  TFVS(I),(TCOUT2(I,J),J=1,13)
  451 FORMAT(1H1,20X,47H THERMAL CONDUCTIVITY-ASME TABLE NO.11 PAGE 281)
C
C     SURFACE  TENSION   AND  LAPLACE  CONSTANT   INTERNATIONAL  BOOK
C                 PAGE  172 -  TABLE  7
C
      WRITE(6,481)
      KU=1
```

```
      DO 480  J=1,16
      TI = TCENT(J)+273.15
      CALL  WASP(1,32,TI,PI,D,H,1)
  480 WRITE(6,482)  TCENT(J),SIGMA,ALC
  481 FORMAT(1H1,20X,75H INTERNATIONAL  BOOK -- TABLE NO.7, SURFACE TENS
     1ION AND LAPLACE CONSTANT     /1H0,24H  T-C   DYNE/CM      MM     /)
  482 FORMAT(1H , F7.0, F8.2, F8.3  )
C
C                   END   TEST   PROGRAM
C
  500 FORMAT(1H1)
      STOP
      END
```

COMPARISON POINTS FOR ASME TABLE 1, REF. 1

Temperature, °F	Pressure, psia	Specific volume, ft^3/lbm		Enthalpy, Btu/lbm		Entropy, Btu/(lbm)(°R)	
		Saturated liquid	Saturated vapor	Saturated liquid	Saturated vapor	Saturated liquid	Saturated vapor
694.	2977.3298	0.033818	0.086042	797.865	1019.980	0.9693	1.1618
682.	2748.8848	0.030727	0.107086	762.559	1060.104	0.9398	1.2003
670.	2535.6538	0.028855	0.126985	735.075	1087.188	0.9166	1.2282
658.	2336.5323	0.027493	0.147265	711.164	1107.807	0.8963	1.2510
646.	2150.5294	0.026420	0.168577	689.416	1124.347	0.8775	1.2707
634.	1976.7792	0.025534	0.191348	669.164	1138.001	0.8599	1.2884
622.	1814.5024	0.024781	0.215942	650.032	1149.472	0.8430	1.3046
610.	1662.9961	0.024126	0.242712	631.787	1159.216	0.8267	1.3196
598.	1521.6270	0.023549	0.272032	614.268	1167.551	0.8108	1.3337
586.	1389.8149	0.023033	0.304307	597.358	1174.705	0.7953	1.3472
574.	1267.0315	0.022568	0.339992	580.970	1180.847	0.7800	1.3601
562.	1152.7839	0.022146	0.379607	565.034	1186.107	0.7650	1.3726
550.	1046.6161	0.021759	0.423747	549.493	1190.589	0.7501	1.3848
538.	948.0988	0.021404	0.473103	534.303	1194.371	0.7353	1.3967
526.	856.8275	0.021075	0.528480	519.422	1197.520	0.7207	1.4084
514.	772.4185	0.020770	0.590820	504.817	1200.088	0.7061	1.4199
502.	694.5060	0.020485	0.661229	490.460	1202.120	0.6916	1.4313
490.	622.7381	0.020218	0.741019	476.323	1203.654	0.6771	1.4426
478.	556.7776	0.019968	0.831743	462.385	1204.721	0.6626	1.4539
466.	496.2980	0.019732	0.935254	448.627	1205.350	0.6481	1.4652
454.	440.9850	0.019510	1.053768	435.030	1205.566	0.6335	1.4765
442.	390.5324	0.019299	1.189955	421.580	1205.392	0.6189	1.4878
430.	344.6448	0.019100	1.347035	408.263	1204.850	0.6042	1.4992
418.	303.0349	0.018910	1.528922	395.068	1203.959	0.5895	1.5106
406.	265.4243	0.018729	1.740390	381.984	1202.738	0.5746	1.5223
394.	231.5432	0.018557	1.987291	369.002	1201.206	0.5597	1.5340
382.	201.1308	0.018393	2.276841	356.114	1199.379	0.5446	1.5460
370.	173.9342	0.018237	2.617991	343.313	1197.275	0.5294	1.5581
358.	149.7103	0.018087	3.021893	330.592	1194.910	0.5140	1.5706
346.	128.2248	0.017944	3.502543	317.946	1192.301	0.4985	1.5833
334.	109.2527	0.017808	4.077606	305.370	1189.462	0.4829	1.5963
322.	92.5786	0.017677	4.769533	292.859	1186.408	0.4671	1.6097
310.	77.9969	0.017552	5.607041	280.409	1183.154	0.4511	1.6234
298.	65.3122	0.017432	6.627140	268.015	1179.713	0.4349	1.6376
286.	54.3393	0.017317	7.877881	255.674	1176.098	0.4186	1.6523
274.	44.9030	0.017208	9.422158	243.381	1172.322	0.4020	1.6675
262.	36.8393	0.017103	11.342943	231.132	1168.395	0.3852	1.6833
250.	29.9942	0.017004	13.750690	218.924	1164.328	0.3682	1.6996
238.	24.2247	0.016908	16.793768	206.753	1160.132	0.3509	1.7167
226.	19.3985	0.016818	20.673405	194.614	1155.816	0.3334	1.7345
214.	15.3935	0.016732	25.665288	182.505	1151.389	0.3156	1.7530
202.	12.0983	0.016650	32.151173	170.422	1146.858	0.2976	1.7724
190.	9.4118	0.016572	40.665682	158.362	1142.232	0.2792	1.7927
178.	7.2427	0.016499	51.966376	146.321	1137.518	0.2605	1.8139
166.	5.5094	0.016430	67.140421	134.298	1132.722	0.2415	1.8362
154.	4.1397	0.016365	87.768644	122.290	1127.852	0.2221	1.8596
142.	3.0699	0.016304	116.182228	110.295	1122.913	0.2024	1.8843
130.	2.2450	0.016249	155.870390	98.311	1117.914	0.1823	1.9102
118.	1.6174	0.016198	212.138521	86.335	1112.859	0.1618	1.9375
106.	1.1469	0.016152	293.189777	74.364	1107.755	0.1409	1.9664
94.	0.7994	0.016112	411.935085	62.394	1102.608	0.1195	1.9969
82.	0.5472	0.016078	589.082329	50.417	1097.424	0.0976	2.0292
70.	0.3673	0.016051	858.522072	38.427	1092.208	0.0753	2.0633
58.	0.2414	0.016032	1276.922623	26.414	1086.967	0.0523	2.0995
46.	0.1552	0.016022	1941.256668	14.377	1081.705	0.0288	2.1379
34.	0.0973	0.016021	3021.535370	2.325	1076.426	0.0047	2.1787

COMPARISON POINTS FOR ASME TABLE 3, REF. 1

(VOLUME, ENTHALPY, ENTROPY FOR PRESSURE LISTED)

TEMPERATURE, °F	1.PSIA			5.PSIA			25.PSIA		
32.	0.01602	0.32	0.0006	0.01602	0.33	0.0006	0.01602	0.39	0.0007
50.	0.01602	18.39	0.0367	0.01602	18.41	0.0367	0.01602	18.46	C.0367
100.	0.01613	68.38	0.1302	0.01613	68.39	0.1302	0.01613	68.44	0.1302
150.	362.76902	1127.69	2.0154	0.01634	118.29	0.2156	0.01634	118.34	C.2156
300.	452.45061	1195.83	2.1152	90.27881	1194.96	1.9369	17.83861	1190.49	1.7550
500.	571.72261	1288.72	2.2237	114.24379	1288.35	2.0460	22.74725	1286.50	1.8671
700.	690.91043	1384.66	2.3144	138.12367	1384.46	2.1369	27.56616	1383.41	1.9588
9C0.	810.07240	1484.02	2.3934	161.97760	1483.88	2.2159	32.35859	1483.21	2.0381
1100.	929.22297	1586.95	2.4640	185.82012	1586.86	2.2865	37.13954	1586.40	2.1089
1300.	1048.36766	1693.58	2.5283	209.65678	1693.51	2.3508	41.91460	1693.18	2.1733
15C0.	1167.50917	1803.96	2.5877	233.49024	1803.91	2.4102	46.68645	1803.66	2.2327

	100.PSIA			200.PSIA			500.PSIA		
32.	0.01602	0.62	0.0007	0.01601	0.92	0.0007	0.01599	1.82	0.0007
50.	0.01602	18.68	0.0367	0.01601	18.97	0.0367	0.01600	19.84	0.0367
1C0.	0.01613	68.64	0.1302	0.01612	68.90	0.1301	0.01611	69.69	0.1299
150.	0.01634	118.53	0.2155	0.01633	118.77	0.2154	0.01632	119.51	0.2151
300.	0.01745	270.14	0.4376	0.01744	270.32	0.4374	0.01742	270.87	0.4369
500.	5.58868	1279.29	1.7087	2.72497	1268.98	1.6241	0.99297	1231.79	1.4925
700.	6.83600	1379.44	1.8034	3.38019	1374.03	1.7236	1.30445	1356.89	1.6114
900.	8.05482	1480.67	1.8839	4.00394	1477.26	1.8056	1.57274	1466.74	1.6988
1100.	9.26186	1584.67	1.9552	4.61550	1582.35	1.8777	1.82748	1575.27	1.7733
1300.	10.46293	1691.94	2.0199	5.22098	1690.28	1.9428	2.07580	1685.25	1.8396
1500.	11.66076	1802.73	2.0795	5.82316	1801.48	2.0026	2.32067	1797.72	1.9001

	1000.PSIA			1500.PSIA			2000.PSIA		
32.	0.01597	3.31	0.0007	0.01594	4.80	0.0007	0.01591	6.28	0.0008
50.	0.01597	21.28	0.0366	0.01595	22.71	0.0365	0.01592	24.14	0.0364
100.	0.01608	71.01	0.1296	0.01606	72.32	0.1293	0.01603	73.63	0.1290
150.	0.01629	120.73	0.2146	0.01627	121.95	0.2142	0.01625	123.17	C.2137
300.	0.01738	271.80	0.4360	0.01735	272.73	0.4351	0.01731	273.67	0.4342
500.	0.02036	487.94	0.6878	0.02025	487.78	0.6857	0.02015	487.69	0.6836
700.	0.60831	1324.80	1.5137	0.37187	1286.91	1.4432	0.24895	1240.21	1.3786
900.	0.76125	1448.31	1.6122	0.48988	1428.71	1.5564	0.35357	1407.85	1.5128
1100.	0.89784	1563.09	1.6909	0.58775	1550.48	1.6400	0.43259	1537.46	1.6018
130C.	1.02740	1676.72	1.7594	0.67795	1668.01	1.7109	0.50325	1659.15	1.6753
15C0.	1.15327	1791.41	1.8212	0.76422	1785.06	1.7739	0.56977	1778.68	1.7396

	5000.PSIA			10000.PSIA			14500.PSIA		
32.	0.01576	15.02	0.0006	0.01552	29.02	-0.0003	0.01532	41.14	-C.0018
50.	0.01577	32.59	0.0357	0.01555	46.26	0.0341	0.01536	58.21	C.0323
100.	0.01590	81.44	0.1271	0.01569	94.26	0.1239	0.01551	105.62	0.1210
150.	0.01611	130.49	0.2110	0.01589	142.63	0.2066	0.01571	153.47	0.2028
300.	0.01711	279.42	0.4292	0.01682	289.30	0.4215	0.01659	298.42	0.4152
5C0.	0.01961	488.31	0.6728	0.01894	492.17	0.6582	0.01848	497.40	0.6475
700.	0.02679	747.13	0.9161	0.02322	717.72	0.8711	0.02177	710.17	C.8485
900.	0.10396	1251.62	1.3194	0.03623	1009.66	1.1023	0.02863	953.03	1.0413
110C.	0.15309	1452.46	1.4579	0.06339	1306.31	1.3066	0.04189	1215.00	1.2210
13C0.	0.18924	1603.91	1.5494	0.08652	1511.71	1.4309	0.05745	1441.21	1.3578
1500.	0.22034	1740.14	1.6228	0.10536	1677.32	1.5201	0.07136	1626.41	1.4576

COMPARISON POINTS FOR ASME TABLE 4, REF. 1

(VOLUME, ENTHALPY, ENTROPY FOR PRESSURE LISTED)

TEMPERATURE, °F	2860.PSIA			3000.PSIA			3060.PSIA		
650.	0.02565	686.64	0.8719	0.02547	685.04	0.8699	0.02540	684.39	0.8691
680.	0.02946	750.28	0.9285	0.02885	745.18	0.9233	0.02863	743.32	0.9214
710.	0.13149	1137.05	1.2648	0.11425	1106.19	1.2357	0.10651	1090.07	1.2209
740.	0.15586	1197.92	1.3162	0.14170	1180.12	1.2982	0.13587	1171.94	1.2901
770.	0.17394	1241.07	1.3518	0.16052	1227.86	1.3375	0.15508	1221.96	1.3313
8C0.	0.18909	1276.31	1.3801	0.17588	1265.61	1.3678	0.17055	1260.89	1.3626

(VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED

	3100.PSIA			3160.PSIA			3200.PSIA		
650.	0.02535	683.97	0.8685	0.02528	683.36	0.8677	0.02524	682.96	0.8672
680.	0.02849	742.16	0.9202	0.02831	740.53	0.9185	0.02819	739.51	0.9174
710.	0.10109	1077.79	1.2097	0.09228	1055.90	1.1901	0.08560	1037.53	1.1738
740.	0.13205	1166.26	1.2845	0.12640	1157.40	1.2759	0.12268	1151.22	1.2700
770.	0.15155	1217.94	1.3271	0.14638	1211.77	1.3207	0.14301	1207.56	1.3164
8C0.	0.16710	1257.70	1.3590	0.16207	1252.84	1.3537	0.15881	1249.55	1.3502

(VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED

	3260.PSIA			3400.PSIA			3500.PSIA		
650.	0.02517	682.37	0.8664	0.02503	681.07	0.8646	0.02493	680.20	0.8634
680.	0.02802	738.06	0.9159	0.02767	735.00	0.9126	0.02745	733.03	C.9104
710.	0.07263	996.74	1.1382	0.03675	834.31	0.9983	0.03427	817.62	0.9835
740.	0.11716	1141.52	1.2608	0.10443	1116.37	1.2375	0.09532	1095.59	1.2186
770.	0.13808	1201.10	1.3099	0.12707	1185.24	1.2942	0.11958	1173.17	1.2826
8C0.	0.15405	1244.54	1.3448	0.14351	1232.48	1.3322	0.13643	1223.51	1.3230

(VOLUME,ENTHALPY,ENTROPY) FOR PRESSURE LISTED

	3600.PSIA			3800.PSIA			3960.PSIA		
650.	0.02483	679.36	0.8623	0.02465	677.79	0.8600	0.02452	676.62	0.8583
680.	0.02724	731.23	0.9084	0.02688	727.98	0.9046	0.02662	725.68	0.9019
710.	0.03294	808.03	0.9748	0.03134	795.78	0.9633	0.03050	788.97	C.9567
740.	0.08601	1071.47	1.1971	0.06610	1007.64	1.1416	0.05088	943.88	1.0870
770.	0.11235	1160.39	1.2704	0.09854	1132.29	1.2444	0.08799	1106.84	1.2215
800.	0.12967	1214.24	1.3137	0.11704	1194.68	1.2946	0.10766	1177.95	1.2786

COMPARISON POINTS FOR ASME TABLE 9, REF. 1

(SPECIFIC HEAT, C_p, Btu/(lbm)($^{\circ}$R))

PSIA	1.	4.	10.	30.	60.	100.	200.	400.	1000.	3000.	6000.	10000.
TEMP F												
32.	1.003	1.003	1.003	1.003	1.003	1.003	1.002	1.001	0.997	0.986	0.971	0.958
300.	0.458	0.461	0.469	0.494	0.536	1.029	1.029	1.028	1.025	1.015	1.002	0.988
700.	0.488	0.488	0.489	0.492	0.496	0.501	0.515	0.547	0.678	6.366	1.526	1.246
1100.	0.524	0.524	0.524	0.525	0.526	0.528	0.532	0.541	0.568	0.681	0.907	1.202
1500.	0.561	0.561	0.562	0.562	0.562	0.563	0.565	0.568	0.578	0.617	0.682	0.771

COMPARISON POINTS FOR TABLE 6a, REF. 2
(VISCOSITY, 10^{-6} kg/(m)(sec))

T,°C	1.BARS	50.BARS	200.BARS	350.BARS	500.BARS	650.BARS	800.BARS
10.	1299.29	1297.83	1293.37	1288.90	1284.44	1279.98	1275.52
50.	544.10	544.61	546.17	547.72	549.27	550.82	552.38
100.	12.11	279.93	282.92	285.91	288.90	291.89	294.88
120.	12.92	230.94	234.12	237.31	240.50	243.68	246.87
140.	13.74	195.97	199.28	202.60	205.91	209.23	212.54
160.	14.55	170.04	173.45	176.86	180.26	183.67	187.08
180.	15.37	150.22	153.69	157.17	160.65	164.13	167.60
200.	16.18	134.63	138.17	141.71	145.25	148.79	152.32
220.	16.99	122.09	125.69	129.28	132.87	136.47	140.06
240.	17.81	111.78	115.42	119.07	122.71	126.36	130.00
260.	18.62	103.12	106.81	110.51	114.21	117.90	121.60
280.	19.44	18.95	99.45	103.19	106.94	110.69	114.44
300.	20.25	21.06	90.52	97.01	103.09	108.95	114.70
320.	21.06	21.83	81.70	88.38	94.39	100.09	105.61
340.	21.88	22.60	73.28	80.63	86.68	92.26	97.60
360.	22.69	23.38	63.46	73.53	79.86	85.38	90.57
400.	24.32	24.95	28.54	57.33	68.92	75.04	79.57
500.	28.39	28.92	31.08	34.89	42.01	51.43	59.39
600.	32.46	32.92	34.60	36.90	40.05	44.15	48.94
700.	36.53	36.94	38.34	40.09	42.22	44.77	47.70

COMPARISON POINTS FOR ASME TABLE 10, REF. 1

(VISCOSITY, 10^{-5} slugs/(ft)(sec))

PSIA T, °F	1.	2.	5.	10.	20.	50.	100.	200.	500.	1000.	2000.	5000.	7500.	10000.	12000.
1500.	8.61	8.61	8.61	8.61	8.62	8.62	8.62	8.63	8.66	8.72	8.83	9.22	9.61	10.06	10.46
1450.	8.38	8.38	8.38	8.38	8.38	8.38	8.39	8.40	8.43	8.48	8.60	9.01	9.42	9.90	10.33
1400.	8.14	8.14	8.14	8.14	8.14	8.15	8.15	8.16	8.20	8.25	8.37	8.80	9.24	9.76	10.22
1350.	7.91	7.91	7.91	7.91	7.91	7.91	7.92	7.93	7.96	8.02	8.14	8.59	9.06	9.63	10.14
1300.	7.67	7.67	7.67	7.67	7.67	7.67	7.68	7.69	7.73	7.79	7.92	8.39	8.90	9.52	10.09
1250.	7.43	7.43	7.43	7.43	7.44	7.44	7.44	7.46	7.49	7.55	7.69	8.19	8.75	9.44	10.07
1200.	7.20	7.20	7.20	7.20	7.20	7.20	7.21	7.22	7.26	7.32	7.46	8.00	8.62	9.40	10.12
1150.	6.96	6.96	6.96	6.96	6.96	6.97	6.97	6.99	7.02	7.09	7.24	7.82	8.51	9.41	10.24
1100.	6.72	6.72	6.72	6.72	6.73	6.73	6.74	6.75	6.79	6.86	7.02	7.65	8.44	9.51	10.48
1050.	6.49	6.49	6.49	6.49	6.49	6.49	6.50	6.51	6.56	6.63	6.79	7.49	8.43	9.73	10.87
1000.	6.25	6.25	6.25	6.25	6.25	6.26	6.27	6.28	6.32	6.40	6.57	7.36	8.52	10.15	11.47
950.	6.02	6.02	6.02	6.02	6.02	6.02	6.03	6.04	6.09	6.17	6.36	7.27	8.80	10.87	12.30
900.	5.78	5.78	5.78	5.78	5.78	5.79	5.79	5.81	5.86	5.94	6.14	7.25	9.49	11.94	13.33
850.	5.54	5.54	5.54	5.54	5.55	5.55	5.56	5.57	5.62	5.71	5.93	7.42	10.88	13.26	14.47
800.	5.31	5.31	5.31	5.31	5.31	5.32	5.32	5.34	5.39	5.49	5.73	8.34	12.80	14.64	15.65
750.	5.07	5.07	5.07	5.07	5.07	5.08	5.09	5.11	5.16	5.26	5.54	11.94	14.62	15.99	16.81
700.	4.84	4.84	4.84	4.84	4.84	4.84	4.85	4.87	4.93	5.04	5.37	14.49	16.08	17.39	18.36
650.	4.60	4.60	4.60	4.60	4.60	4.61	4.62	4.64	4.70	4.82	5.26	16.52	17.98	19.30	20.31
600.	4.36	4.36	4.36	4.36	4.37	4.37	4.38	4.40	4.47	4.61	16.80	18.78	20.22	21.59	22.65
550.	4.13	4.13	4.13	4.13	4.13	4.12	4.12	4.11	4.08	4.01	19.89	20.97	21.88	22.78	23.51
500.	3.89	3.89	3.89	3.89	3.89	3.88	3.87	3.85	3.78	21.62	21.97	23.04	23.93	24.81	25.52
450.	3.65	3.65	3.65	3.65	3.65	3.64	3.62	3.59	24.04	24.21	24.56	25.61	26.48	27.35	28.04
400.	3.42	3.42	3.42	3.42	3.41	3.40	3.37	3.33	27.39	27.56	27.90	28.92	29.77	30.63	31.31
350.	3.18	3.18	3.18	3.18	3.17	3.15	3.12	31.78	31.88	32.05	32.38	33.38	34.21	35.05	35.71
300.	2.95	2.95	2.95	2.95	2.93	2.91	38.08	38.11	38.21	38.37	38.69	39.66	40.47	41.27	41.92
250.	2.71	2.71	2.71	2.71	2.69	47.48	47.49	47.52	47.62	47.77	48.08	49.00	49.76	50.53	51.15
200.	2.47	2.47	2.47	2.47	62.49	62.50	62.51	62.54	62.62	62.76	63.04	63.87	64.57	65.27	65.82
150.	2.24	2.24	88.81	88.81	88.81	88.82	88.83	88.85	88.92	89.03	89.24	89.90	90.44	90.98	91.42
100.	141.48	141.48	141.48	141.48	141.48	141.49	141.49	141.50	141.51	141.55	141.61	141.80	141.95	142.11	142.23
50.	269.99	269.99	269.99	269.98	269.98	269.97	269.95	269.90	269.78	269.57	269.14	267.87	266.82	265.76	264.92
32.	363.91	363.91	363.91	363.91	363.90	363.87	363.83	363.75	363.50	363.08	362.25	359.75	357.67	355.59	353.92

COMPARISON POINTS FOR TABLE 6a, REF. 2
(THERMAL CONDUCTIVITY, 10^{-2} W/(m)(K))

P-BARS T,°C	1.	10.	25.	50.	100.	150.	200.	250.	300.	350.	400.	450.	500.
10.	58.70	58.78	58.91	59.12	59.53	59.94	60.33	60.70	61.07	61.41	61.75	62.07	62.38
50.	64.33	64.41	64.53	64.74	65.14	65.52	65.89	66.24	66.58	66.90	67.20	67.49	67.76
100.	2.45	68.14	68.24	68.42	68.77	69.11	69.45	69.77	70.09	70.40	70.69	70.98	71.27
120.	2.61	68.72	68.82	68.99	69.33	69.66	69.98	70.31	70.62	70.93	71.24	71.54	71.84
140.	2.77	68.82	68.92	69.09	69.42	69.75	70.08	70.41	70.73	71.06	71.38	71.70	72.01
160.	2.95	68.46	68.57	68.74	69.09	69.43	69.77	70.12	70.46	70.80	71.14	71.48	71.82
180.	3.13	3.41	67.77	67.96	68.34	68.72	69.09	69.47	69.83	70.20	70.56	7C.93	71.28
200.	3.31	3.51	66.54	66.76	67.20	67.63	68.06	68.47	68.88	69.28	69.68	70.07	70.44
220.	3.51	3.66	64.86	65.13	65.66	66.17	66.67	67.16	67.62	68.07	68.50	68.92	69.32
240.	3.71	3.84	4.25	63.02	63.69	64.33	64.93	65.51	66.05	66.57	67.05	67.50	67.92
260.	3.91	4.03	4.34	60.39	61.25	62.05	62.81	63.51	64.16	64.76	65.31	65.81	66.26
280.	4.12	4.23	4.48	5.27	58.24	59.27	60.23	61.11	61.92	62.64	63.29	63.86	64.35
300.	4.34	4.44	4.65	5.25	54.51	55.87	57.10	58.23	59.24	60.14	60.93	61.61	62.17
320.	4.56	4.65	4.84	5.32	7.52	51.62	53.24	54.71	56.01	57.17	58.16	59.00	59.69
340.	4.78	4.87	5.05	5.46	7.00	46.21	48.35	50.29	52.01	53.52	54.83	55.93	56.82
360.	5.01	5.10	5.27	5.62	6.81	9.50	41.22	44.44	46.79	48.82	50.63	52.26	53.70
400.	5.48	5.57	5.72	6.02	6.86	8.22	10.73	15.49	26.38	35.11	38.85	41.51	43.77
500.	6.73	6.82	6.96	7.20	7.76	8.43	9.26	10.29	11.58	13.22	15.32	17.96	20.22
600.	8.05	8.14	8.27	8.50	8.98	9.51	10.09	10.73	11.42	12.19	13.02	13.94	14.94
70C.	9.42	9.50	9.63	9.85	10.31	10.79	11.29	11.81	12.36	12.93	13.52	14.14	14.79

COMPARISON POINTS FOR ASME TABLE 11, REF. 1

(THERMAL CONDUCTIVITY, 10^{-3} Btu/(lbm)(ft)(^{o}R))

PSIA T, ^{o}F	1.	2.	5.	10.	20.	50.	100.	200.	500.	1000.	2000.	5000.	7500.
1500.	63.72	63.72	63.72	63.72	63.79	63.89	64.06	64.40	65.43	67.17	70.73	82.08	92.27
1450.	61.50	61.50	61.50	61.50	61.56	61.67	61.84	62.18	63.21	64.96	68.55	80.12	90.67
1400.	59.27	59.27	59.27	59.27	59.34	59.44	59.61	59.95	60.99	62.74	66.37	78.22	89.21
1350.	57.04	57.04	57.04	57.04	57.11	57.21	57.38	57.73	58.77	60.53	64.21	76.39	87.95
1300.	54.82	54.82	54.82	54.82	54.89	54.99	55.16	55.51	56.55	58.33	62.06	74.66	86.95
1250.	52.61	52.61	52.61	52.61	52.68	52.78	52.95	53.30	54.34	56.14	59.93	73.07	86.33
1200.	50.41	50.41	50.41	50.41	50.48	50.58	50.75	51.09	52.15	53.96	57.83	71.68	86.26
1150.	48.22	48.22	48.22	48.22	48.29	48.39	48.56	48.91	49.97	51.81	55.77	70.56	87.01
1100.	46.05	46.05	46.05	46.05	46.12	46.22	46.39	46.74	47.81	49.68	53.77	69.85	89.08
1050.	43.90	43.90	43.90	43.90	43.97	44.07	44.24	44.59	45.67	47.58	51.84	69.77	93.39
1000.	41.78	41.78	41.78	41.78	41.84	41.95	42.12	42.47	43.56	45.51	50.01	70.72	103.03
950.	39.68	39.68	39.68	39.68	39.75	39.85	40.03	40.38	41.49	43.50	48.32	73.53	115.72
900.	37.61	37.61	37.61	37.61	37.68	37.79	37.96	38.32	39.45	41.55	46.83	80.13	138.89
850.	35.58	35.58	35.58	35.58	35.65	35.76	35.93	36.29	37.45	39.69	45.65	96.65	178.93
800.	33.59	33.59	33.59	33.59	33.66	33.76	33.94	34.31	35.51	37.93	44.99	129.61	216.27
750.	31.64	31.64	31.64	31.64	31.71	31.81	31.99	32.37	33.64	36.34	45.26	202.45	258.72
700.	29.73	29.73	29.73	29.73	29.80	29.91	30.09	30.48	31.85	35.01	47.53	262.30	300.07
650.	27.87	27.87	27.87	27.87	27.94	28.05	28.24	28.64	30.18	34.12	55.63	304.32	326.85
600.	26.07	26.07	26.07	26.07	26.14	26.24	26.44	26.88	28.69	34.10	301.91	333.84	349.42
550.	24.31	24.31	24.31	24.31	24.38	24.50	24.70	25.20	27.50	36.09	333.79	356.27	368.12
500.	22.62	22.62	22.62	22.62	22.69	22.81	23.04	23.64	26.90	350.92	357.54	374.00	383.83
450.	20.98	20.98	20.98	20.98	21.06	21.19	21.47	22.27	368.22	370.70	375.45	388.08	396.72
400.	19.42	19.42	19.42	19.42	19.49	19.65	20.03	21.28	383.22	385.06	388.66	398.86	406.68
350.	17.91	17.91	17.91	17.91	18.00	18.22	18.82	392.26	393.15	394.64	397.60	406.33	413.46
300.	16.49	16.49	16.49	16.49	16.60	16.97	397.16	397.43	398.24	399.59	402.27	410.21	416.73
250.	15.13	15.13	15.13	15.13	15.33	397.16	397.30	397.57	398.39	399.73	402.39	410.05	416.08
200.	13.85	13.85	13.85	13.85	391.87	391.96	392.11	392.40	393.28	394.72	397.51	405.25	410.95
150.	12.66	12.66	380.87	380.89	380.92	381.02	381.18	381.50	382.46	384.02	387.02	395.08	400.69
100.	363.64	363.64	363.65	363.67	363.70	363.80	363.98	364.32	365.34	367.00	370.19	378.67	384.48
50.	339.51	339.52	339.53	339.54	339.58	339.68	339.86	340.20	341.23	342.91	346.17	355.06	361.44
32.	329.00	329.00	329.01	329.03	329.06	329.16	329.33	329.67	330.69	332.35	335.59	344.59	351.28

COMPARISON POINTS FOR TABLE 7, REF. 2
(SURFACE TENSION AND LAPLACE CONSTANT)

T-C	DYNE/CM	MM
10.	74.24	2.752
50.	67.93	2.648
100.	58,78	2.502
120.	54.85	2.437
140.	50.79	2.367
160.	46.59	2.292
180.	42.26	2.211
200.	37.81	2.121
220.	33.23	2.022
240.	28.56	1.912
260.	23.82	1.787
280.	19.07	1.646
300.	14.39	1.484
320.	9.89	1.294
340.	5.71	1.060
360.	2.03	0.734

APPENDIX G

METASTABLE SUBROUTINE (PMETAS)

Although property measurements for other than stable states are very difficult to make, metastable states are of interest in heat-transfer and fluid-flow calculations. The fundamental equation

$$\psi = \psi_0(T) + RT[\ln \rho + \rho Q(\rho, \tau)]$$

represents a continuum of single-phase states between the saturated liquid and saturated vapor states which can be classified as either metastable or unstable (as for the Van der Waals equation). Consequently, properties of the superheated liquid and supersaturated vapor can be determined. It is pointed out in reference 3 that between 300° C and the critical temperature, the nonstable states as determined by the fundamental equation have a single maximum and minimum. At lower temperatures, more than one pair of extremum exists for which the authors of reference 3 attach no significance.

The subroutine PMETAS (KU, T, D, P, KR) is provided to illustrate to the user of WASP how the metastable and unstable states can be determined. Given a density D and a temperature T (KU and KR have their usual meanings) the pressure P is returned

$$P = \rho RT\left[1 + \rho Q(\rho, \tau) + \rho^2 \frac{\partial Q(\rho, \tau)}{\partial \rho}\right]$$

The user can then formulate a locus of maximum and minimum points, as for the Van der Waals equation, and determine if the point is stable, metastable, or unstable. (Note that PMETAS will also return stable points provided D and T represent a stable point.) Examples of the metastable and unstable loci are given as figures 14.

```
$IBFTC PMETA
      SUBROUTINE PMETAS(KU,T,D,P,KR)
C             ----------------------4/10-72  ---------------------
C
C
C     THIS ROUTINE CALCULATES PRESSURE FOR ANY T INPUT AND D INPUT.
C                  THIS ROUTINE DOES NOT DEFINE A REGION AND IS NOT
C                  CALLED BY -WASP-. THE USER CALLS IT DIRECTLY AND
C                  IT CAN BE USED IN THE METASTABLE STATE.
C
C
      COMMON /CONV3/PCONV(5)
      COMMON /TPARAM/TS
      COMMON /CONSTS/ TAUC,RHOA,RHOB,TAUA,E,R
      COMMON /CHECKS/ DCH1,DCH2,PCH1,PCH2,PCH3,TCH1,TCH2,TCH3,DST,TST,
     1HSCH1,HSCH2
      COMMON /IERROR/IROUT
      DS= DCHECK(KU,D)
      TS= TCHECK(KU,KR,T)
C
      IROUT= 2
C
C                 ONE EQUATION FOR ALL REGIONS
C
      CALL QMUST(DS)
      CALL QMUST2(TS)
      PS= 1000.*R*DS/TS*(1.+DS*(QCALC(TS)+DS*QDT(DS,TS)))
   90 P= PS*PCONV(KU)
      RETURN
      END
```

APPENDIX H

THERMODYNAMIC RELATIONS AND DERIVATIVES

The symbols C_p, C_v, H, P, R, S, T, and ρ have the same meaning as defined elsewhere in this report. The other symbols used exclusively in this appendix are defined as follows:

$A = E - TS$	Helmholtz free energy or work content
E	internal energy
$F = H - TS$	Gibbs free energy or free energy
K	equilibrium constant
V	specific volume

To illustrate the facility of the partial derivatives, Roder and Weber (ref. 17) give five which are useful to engineers:

Specific heat input:

$$V\left(\frac{\partial H}{\partial V}\right)_P = \rho C_p \left[\frac{\left(\frac{\partial P}{\partial \rho}\right)_T}{\left(\frac{\partial P}{\partial T}\right)_\rho}\right]$$

Energy derivative:

$$V\left(\frac{\partial P}{\partial E}\right)_V = \frac{1}{\rho C_v}\left(\frac{\partial P}{\partial T}\right)_\rho$$

Isothermal bulk modulus:

$$V\left(\frac{\partial P}{\partial V}\right)_T = - \rho\left(\frac{\partial P}{\partial \rho}\right)_T$$

Volume expansivity:

$$\frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P = \frac{1}{\rho}\frac{\left(\frac{\partial P}{\partial T}\right)_\rho}{\left(\frac{\partial P}{\partial \rho}\right)_T}$$

The background material necessary to derive these and other parameters as the Joule-Thomson coefficient

$$\mu = \frac{1}{\rho C_p}\left[\frac{T}{\rho}\frac{\left(\frac{\partial P}{\partial T}\right)_\rho}{\left(\frac{\partial P}{\partial \rho}\right)_T} - 1\right]$$

can be found in most thermodynamic texts.

WASP provides the partial derivatives $(\partial P/\partial \rho)_T$ and $(\partial P/\partial T)_\rho$. With the aid of the following thermodynamic derivatives and the Bridgeman Tables, any thermodynamic parameter can be found. The following thermodynamic tables were taken from reference 18.

Differential energy formulas:

$$dE = T\,dS - P\,dV$$

$$dH = T\,dS + V\,dP$$

$$dA = -\,S\,dT - P\,dV$$

$$dF = -\,S\,dT + V\,dP$$

Maxwell relations:

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

$$\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

$$\left(\frac{\partial S}{\partial P}\right)_T = -\left(\frac{\partial V}{\partial T}\right)_P$$

Energy-function derivatives:

$$\left(\frac{\partial E}{\partial S}\right)_V = \left(\frac{\partial H}{\partial S}\right)_P = T$$

$$\left(\frac{\partial E}{\partial V}\right)_S = \left(\frac{\partial A}{\partial V}\right)_T = -P$$

$$\left(\frac{\partial H}{\partial P}\right)_S = \left(\frac{\partial F}{\partial P}\right)_T = V$$

$$\left(\frac{\partial F}{\partial T}\right)_P = \left(\frac{\partial A}{\partial T}\right)_V = -S$$

Heat-capacity relations:

$$C_V = \left(\frac{\partial E}{\partial T}\right)_V = T\left(\frac{\partial S}{\partial T}\right)_V$$

$$C_P = \left(\frac{\partial H}{\partial T}\right)_P = T\left(\frac{\partial S}{\partial T}\right)_P$$

$$C_P - C_V = -T\left(\frac{\partial V}{\partial T}\right)_P^2\left(\frac{\partial P}{\partial V}\right)_T$$

$$C_P - C_{sat} = T\left(\frac{\partial V}{\partial T}\right)_P\left(\frac{\partial P}{\partial T}\right)_{sat}$$

$$\left(\frac{\partial C_V}{\partial V}\right)_T = T\left(\frac{\partial^2 P}{\partial T^2}\right)_V$$

$$\left(\frac{\partial C_P}{\partial P}\right)_T = - T\left(\frac{\partial^2 V}{\partial T^2}\right)_P$$

Effect of P or V on H or E:

$$\left(\frac{\partial H}{\partial P}\right)_T = V - T\left(\frac{\partial V}{\partial T}\right)_P$$

$$\left(\frac{\partial E}{\partial V}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_V - P$$

Temperature effect on $\Delta F/T = - R \ln K$:

$$\left[\frac{\partial\left(\frac{\Delta F}{T}\right)}{\partial T}\right]_P = - R\,\frac{\partial \ln K}{\partial T} = - \frac{\Delta H}{T^2}$$

Partial molal quantities, where Y is any extensive quantity:

$$\bar{y}_1 = \left(\frac{\partial Y}{\partial n_1}\right)_{P, T, n_2, n_3, \ldots}$$

$$Y = n_1\bar{y}_1 + n_2\bar{y}_2 + \ldots$$

$$x_1\left(\frac{\partial \bar{y}_1}{\partial x_1}\right) + x_2\left(\frac{\partial \bar{y}_2}{\partial x_1}\right) + \ldots = 0$$

$$\left(\frac{\partial \bar{y}_i}{\partial n_j}\right) = \frac{\partial^2 Y}{\partial n_i\, \partial n_j} = \left(\frac{\partial \bar{y}_j}{\partial n_i}\right)$$

The so-called Bridgeman Tables are summarized as follows:

$$(\partial T)_P = -(\partial P)_T = 1$$

$$(\partial V)_P = -(\partial P)_V = \left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial S)_P = -(\partial P)_S = \frac{C_P}{T}$$

$$(\partial E)_P = -(\partial P)_E = C_P - P\left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial H)_P = -(\partial P)_H = C_P$$

$$(\partial F)_P = -(\partial P)_F = -S$$

$$(\partial A)_P = -(\partial P)_A = -\left[S + P\left(\frac{\partial V}{\partial T}\right)_P\right]$$

$$(\partial V)_T = -(\partial T)_V = -\left(\frac{\partial V}{\partial P}\right)_T$$

$$(\partial S)_T = -(\partial T)_S = \left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial E)_T = -(\partial T)_E = T\left(\frac{\partial V}{\partial T}\right)_P + P\left(\frac{\partial V}{\partial P}\right)_T$$

$$(\partial H)_T = -(\partial T)_H = -V + T\left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial F)_T = -(\partial T)_F = -V$$

$$(\partial A)_T = -(\partial T)_A = P\left(\frac{\partial V}{\partial P}\right)_T$$

$$(\partial S)_V = -(\partial V)_S = \frac{1}{T}\left[C_P\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2\right]$$

$$(\partial E)_V = -(\partial V)_E = C_P\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2$$

$$(\partial H)_V = -(\partial V)_H = C_P\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2 - V\left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial F)_V = -(\partial V)_F = -\left[V\left(\frac{\partial V}{\partial T}\right)_P + S\left(\frac{\partial V}{\partial P}\right)_T\right]$$

$$(\partial A)_V = -(\partial V)_A = -S\left(\frac{\partial V}{\partial P}\right)_T$$

$$(\partial E)_S = -(\partial S)_E = \frac{P}{T}\left[C_P\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2\right]$$

$$(\partial H)_S = -(\partial S)_H = -\frac{VC_P}{T}$$

$$(\partial F)_S = -(\partial S)_F = -\frac{1}{T}\left[VC_P - ST\left(\frac{\partial V}{\partial T}\right)_P\right]$$

$$(\partial A)_S = -(\partial S)_A = \frac{1}{T}\left\{P\left[C_P\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2\right] + ST\left(\frac{\partial V}{\partial T}\right)_P\right\}$$

$$(\partial H)_E = -(\partial E)_H = -V\left[C_P - P\left(\frac{\partial V}{\partial T}\right)_P\right] - P\left[C_P\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2\right]$$

$$(\partial F)_E = -(\partial E)_F = -V\left[C_P - P\left(\frac{\partial V}{\partial T}\right)_P\right] + S\left[T\left(\frac{\partial V}{\partial T}\right)_P + P\left(\frac{\partial V}{\partial P}\right)_T\right]$$

$$(\partial A)_E = -(\partial E)_A = P\left[(C_P + S)\left(\frac{\partial V}{\partial P}\right)_T + T\left(\frac{\partial V}{\partial T}\right)_P^2\right] + ST\left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial F)_H = -(\partial H)_F = -V(C_P + S) + TS\left(\frac{\partial V}{\partial T}\right)_P$$

$$(\partial A)_H = -(\partial H)_A = -\left[S + P\left(\frac{\partial V}{\partial T}\right)_P\right]\left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right] + PC_P\left(\frac{\partial V}{\partial P}\right)_T$$

$$(\partial A)_F = -(\partial F)_A = -S\left[V + P\left(\frac{\partial V}{\partial P}\right)_T\right] - PV\left(\frac{\partial V}{\partial T}\right)_P$$

REFERENCES

1. Meyer, C. A.; McClintock, R. B.; Silverstri, G. J.; Spencer, R. C., Jr.: Thermodynamic and Transport Properties of Steam. 1967 ASME Steam Tables. Second ed., ASME, 1967.

2. Schmidt, Ernst: Properties of Water and Steam in SI-Units. Springer-Verlag, New York, Inc., 1969.

3. Keyes, F. G.; Keenan, J. H.; Hill, P. G.; and Moore, J. G.: A Fundamental Equation for Liquid and Vapor Water. Presented at the Seventh International Conference on the Properties of Steam, Tokyo, Japan, Sept. 1968.

4. Benedict, Manson; Webb, George B.; and Rubin, Louis C.: An Empirical Equation for Thermodynamic Properties of Light Hydrocarbons and Their Mixtures. I. Methane, Ethane, Propane and n-Butane. J. Chem. Phys., vol. 8, no. 4, Apr. 1940, pp. 334-345.

5. Strobridge, Thomas R.: The Thermodynamic Properties of Nitrogen from 64^o to 300^o K Between 0.1 and 200 Atmospheres. Tech. Note 129, National Bureau of Standards, Jan. 1962.

6. Roder, Hans M.; and Goodwin, Robert D.: Provisional Thermodynamic Functions for Para-Hydrogen. Tech. Note 130, National Bureau of Standards, Dec. 1961.

7. Bender, E.: Equations of State Exactly Representing the Phase Behavior of Pure Substances. Proceedings of the Fifth Symposium on Thermophysical Properties, ASME, 1970, pp. 227-235.

8. Hendricks, R. C.; Baron, A.; Peller, I.; and Pew, K. J.: GASP - A Computer Code for Calculating the Thermodynamic and Transport Properties for Eight Fluids - Helium, Methane, Neon, Nitrogen, Carbon Monoxide, Oxygen, Argon, Carbon Dioxide. Presented at the XIII International Congress of Refrigeration, NAS/NRC, Washington, D.C., Aug. 27 - Sept. 3, 1971.

9. Jossi, John A.; Stiel, Leonard I.; and Thodos, George: The Viscosity of Pure Substances in the Dense Gaseous and Liquid Phases. AIChE J., vol. 8, no. 1, Mar. 1962, pp. 59-63.

10. Svehla, Roger A.: Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures. NASA TR R-132, 1962.

11. Le Neindre, B.; Bury, P.; Tufeu, R.; Johannin, P.; and Vodar, B.: The Thermal Conductivity Coefficients of Carbon Dioxide at High Temperature and High Pressure. Ninth Conference on Thermal Conductivity. Howard R. Shanks, ed. USAEC Rep. CONF-691002, Mar. 1970, pp. 69-93.

12. Sengers, J. V.; and Keyes, P. H.: Scaling of the Thermal Conductivity Near the Gas-Liquid Critical Point. Tech. Rep. 71-061, Univ. of Maryland, 1971.

13. Hendricks, R. C.; and Baron, A.: Prediction of the Thermal Conductivity Anomaly of Simple Substances in the Critical Region. NASA TM X-52955, 1971.

14. Sengers, J. V.: Transport Properties of Gases and Binary Liquids Near the Critical Point. NASA CR-2112, 1972.

15. Brokaw, Richard S.: Statistical Mechanical Theories of Transport Properties. Presented at the International Conference on the Properties of Steam, Tokyo, Japan, Sept. 9-13, 1968.

16. Hendricks, R. C.; Simoneau, R. J.; and Smith, R. V.: Survey of Heat Transfer to Near-Critical Fluids. Advances in Cryogenic Engineering. Vol. 15. K. D. Timmerhaus, ed., Plenum Press, 1970, pp. 197-237.

17. Roder, Hans M.; and Weber, Lloyd A., eds.: ASRDI Oxygen Technology Survey. Vol. I: Thermophysical Properties. NASA SP-3071, 1972.

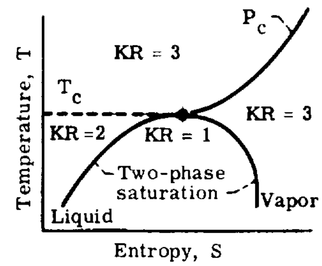
18. Lewis, Gilbert N.; and Randall, Merle: Thermodynamics. Second ed., McGraw-Hill Book Co., Inc., 1961, pp. 665-668.

TABLE I. - OPERATIONS SHEET FOR SUBROUTINE WASP[a]

```
COMMON/PROPTY/KU, DL, DV, HL, HV, S, SL, SV, CV, CVL, CVV, CP, CPL, CPV, GAMMA, GAMMAL, GAMMAV, C,
CL, CVP, MU, MUL, MUV, K, KL, KV, SIGMA, EXCL, EXCV, EXCESK
REAL MU, MUL, MUV, K, KL, KV

CALL WASP (KS, KP, T, P, D, H, KR)
```

- KR — Region
  - KR=0 Unknown, check KR returned
  - KR=1 Saturation
  - KR=2 Liquid
  - KR=3 Gas and/or fluid
- H — Enthalpy, J/g
- D — Density, g/cm^3
- P — Pressure, MN/m^2
- T — Temperature, K



- KP — Thermodynamic and transport properties[b]

KP=0		Only P, ρ, and T returned
KP=1	H	Enthalpy, J/g; (H), (HL), (HV)
KP=2	S	Entropy, J/(g)(K); (S), (SL), (SV)
KP=4	C_v	Specific heat at constant volume, J/(g)(K); (CV), (CVL), (CVV)
	C_p	Specific heat at constant pressure, J/(g)(K); (CP), (CPL), (CPV)
	γ	Ratio of specific heats, C_p/C_v; (GAMMA), (GAMMAL), (GAMMAV)
	c	Sonic velocity, cm/sec; (C), (CL), (CVP)
KP=8	μ	Dynamic viscosity, g/(cm)(sec); (MU), (MUL), (MUV)
KP=16	k	Thermal conductivity, W/(cm)(K); (K), (KL), (KV)
KP=32	σ	Surface tension, dyne/cm; (SIGMA)

- KS — Input specification of independent properties

KS=1	ρ = f(T, P); given T, P find ρ
KS=2	P = f(T, ρ); given T, ρ find P
KS=3	T = f(P, ρ); given P, ρ find T
KS=4	T, ρ = f(P, H); given P, H find T, ρ
KS=5	T, ρ = f(P, S); given P, S find T, ρ

[a]Notes:

1. The units indicator, KU, must be set such that $1 \le KU \le 5$ or no valid property values can be determined. See table II.
2. Reset KR $\neq$ 1 for each call to WASP to be assured of nonsaturation calculations (unless $T = T_{sat}$ and $P = P_{sat}$).
3. Sample problem:

```
COMMON/PROPTY/KU, etc. (as above)
REAL MU, etc. (as above)
KU=1
KR=0
T=773.0
D=0.178
Call WASP (2, 31, T, P, D, H, KR)
```

WASP will return P = 40. MN/m^2, KR = 3, H = 2902.4, and the following values in COMMON: S = 5.4689, CV = 2.4503, CP = 5.7893, GAMMA = 2.363, C = 57415.4, MU = 0.3682×10^{-3}, K = 0.1534×10^{-2}.

[b]KP input is $\sum$ KP options if more than one property is requested. For example, if enthalpy and entropy are desired, set KP equal to 3.

TABLE II. - UNITS SPECIFICATION

Physical quantity	Units specification		
	KU=1	KU=2	KU=3
Temperature	K	K	^{o}R
Density	g/cm^3	g/cm^3	lbm/ft^3
Pressure	MN/m^2	atmospheres	psia
Enthalpy	joule/g	joule/g	Btu/lbm
Entropy, specific heat	joule/(g)(K)	joule/(g)(K)	Btu/(lbm)(^{o}R)
Sonic velocity	cm/sec	cm/sec	ft/sec
Dynamic viscosity	g/(cm)(sec)	g/(cm)(sec)	lbm/(ft)(sec)
Thermal conductivity	joule/(cm)(sec)(K)	joule/(cm)(sec)(K)	Btu/(ft)(sec)(^{o}R)
Surface tension	dyne/cm	dyne/cm	lbf/ft

[a]KU=4, 5 permit the user to work in other units; however, the proper conversions must be entered into BLOCK DATA. To add special set of units for KU=4 or KU=5:

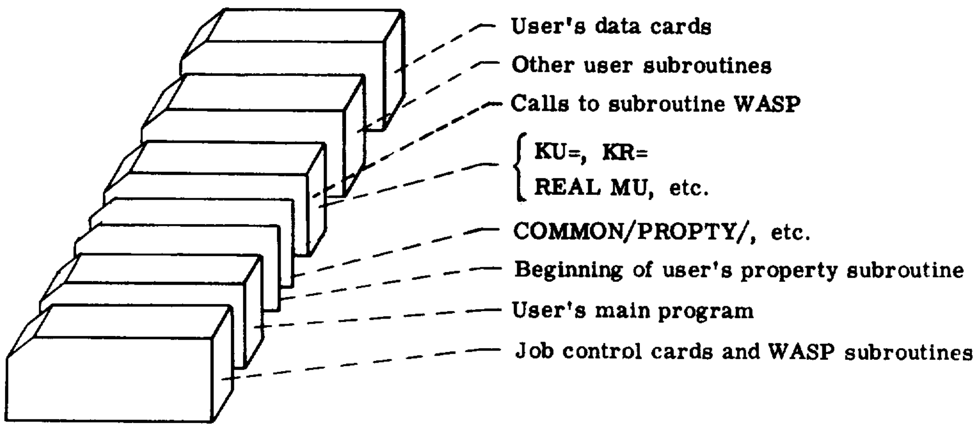
(1) User's program must contain following COMMON

/CONV1/DCONV(5)
/CONV2/TCONV(5)
/CONV3/PCONV(5)
/CONV4/SCONV(5)
/CONV5/CCONV(5)
/CONV6/HCONV(5)
/CONV7/MCONV(5)
/CONV8/KCONV(5)
/CONV9/STCONV(5)
REAL MCONV, KCONV

or modify BLOCK DATA subprogram directly (See appendix E for listing of BLOCK DATA.)

(2) Store conversion factors in fourth and/or fifth position of each array such that (D in input unit desired)/DCONV(4) = g/cm^3, etc. All conversion factors must change input to units of KU=1. For output then, (D in g/cm^3)*DCONV(4) = (D in desired units).

TABLE III. - PROGRAM ASSEMBLY



The subroutines in WASP may be loaded in any order with respect to the user's program. To run successfully, there must appear in at least one user subroutine the following:

(1) COMMON/PROPTY/, etc.
REAL MU, etc.

(2) KU=1 (or 2, 3, 4, 5)

(3) Other input variable specifications

(4) Calls to subroutine WASP

The COMMON/PROPTY/, of course, must be in the main program or subroutine where the user expects answers to be returned from WASP. It could be in several or all user subroutines.

TABLE IV. - COEFFICIENTS OF Q-FUNCTION, ψ_0-FUNCTION, AND VAPOR PRESSURE CURVE

(a) Coefficients of Q-function

i	j = 1	2	3	4	5	6	7
	Coefficients, A_{ij}						
1	29.492937	-5.1985860	6.8335354	-0.1564104	-6.3972405	-3.9661401	-0.69048554
2	-132.13917	7.7779182	-26.149751	-0.72546108	26.409282	15.453061	2.7407416
3	274.64632	-33.301902	65.326396	-9.2734289	-47.740374	-29.142470	-5.1028070
4	-360.93828	-16.254622	-26.181978	4.3125840	56.323130	29.568796	3.9636085
5	342.18431	-177.31074	0	0	0	0	0
6	-244.50042	127.48742					
7	155.18535	137.46153					
8	5.9728487	155.97836					
9	-410.30848	337.31180	-137.46618	6.7874983	136.87317	79.847970	13.041253
10	-416.05860	-209.88866	-733.96848	10.401717	645.81880	399.17570	71.531353

(b) Coefficients of ψ_0-function

i	Coefficients C_i
1	1855.3865
2	3.278642
3	-.00037903
4	46.174
5	-1.02117

(c) Coefficients of vapor pressure curve

i	Coefficients D_i
1	2.9304370
2	-2309.5789
3	$.34522497\times10^{-1}$
4	$-.13621289\times10^{-3}$
5	$.25878044\times10^{-6}$
6	$-.24709162\times10^{-9}$
7	$.95937646\times10^{-13}$

TABLE V. - NECESSARY AND OPTIONAL ROUTINES

(a) Necessary routines

NAME (* indicates multiple entry)	Reason
BLOCK DATA	Stores coefficients for the fundamental equation
*(CHECK, TCHECK, PCHECK, DCHECK)	Performs region and limit checks for all subroutines; converts user's units to internal program units
ROOT ROOTX SOLVE	Mathematical routines used in all iterative solutions necessary to calculation of properties
QCALC *(QMUST, QMUST2) QTD *(QDTA, QDT) Q2T2D *(Q2DTA, Q2DT) *(Q2D2TA, Q2D2T)	Q-function and derivatives used in equation-of-state calculations (See equations used by all KS and KP options.)
DENS PSSS *(DSF, DDSF)	Used for KS=1 request and to determine region number for most other KS and KP options

(b) Optional routines

NAME (* indicates multiple entry)	KS or KP option involved	Statement numbers in subroutine WASP	Additional conditions for removal
PRESS	KS=2	20	None
TEMP TSS *(TSSF, DTSSF) *(TSF, DTSF)	KS=3 (also KS=4 and KS=5)	30 40 45	Must also remove TEMPPH, TEMPPS, TSHF, and TPSF
TEMPPH *(TSHF, TPSF)	KS=4	40	None
TEMPPS *(TSHF, TPSF)	KS=5	45	None
ENTH	KP=1 (also KS=4)	60 40	Must also remove TEMPPH and TSHF
ENT	KP=2 KS=5	100 45	Must also remove TEMPPS and TPSF
CPPRL	KP=4	130 to 140	None
VISC	KP=8	160 to 170	None
THERM	KP=16	180 to 190	None
SURF	KP=32	240	None

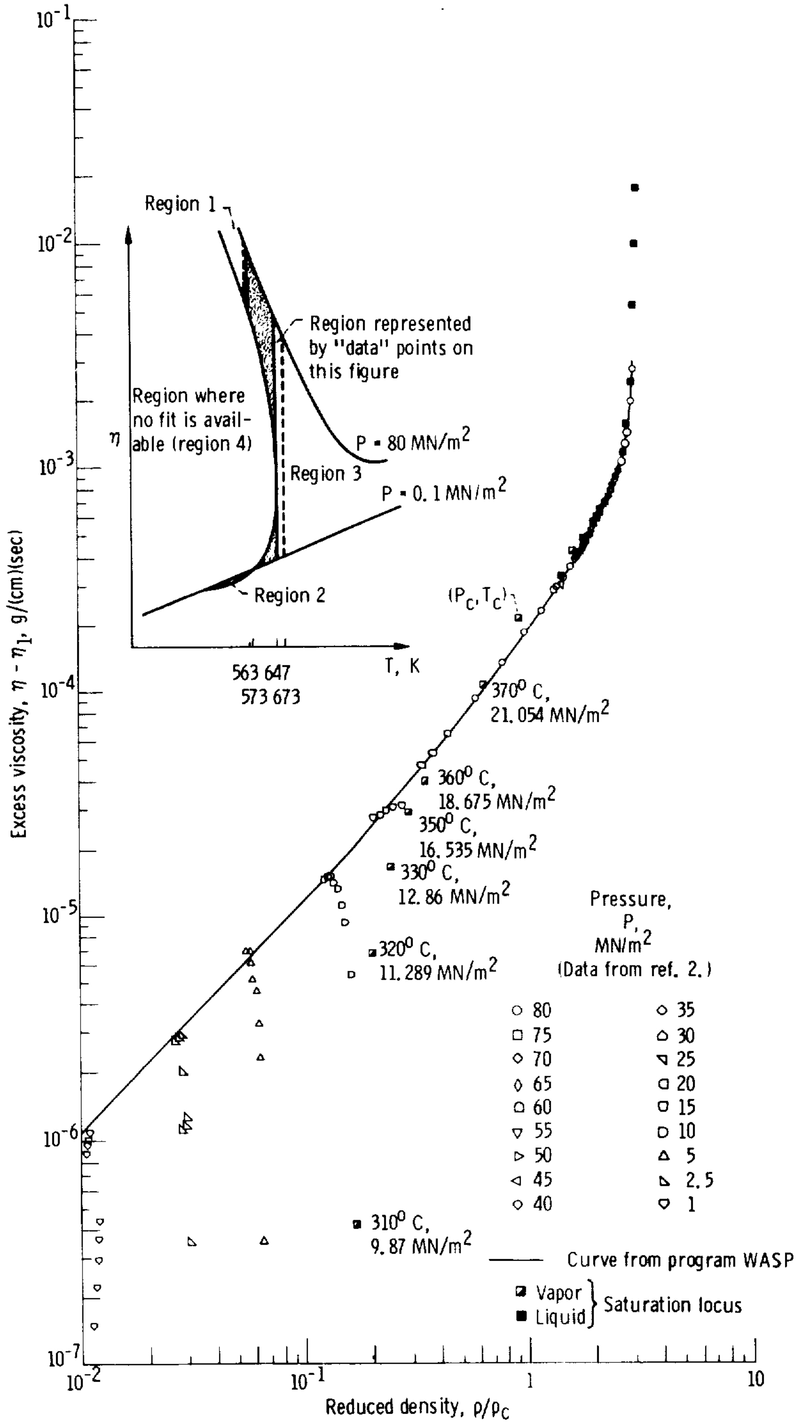


Figure 1. - Excess viscosity as function of reduced density for region 563 K ≤ T ≤ 673 K.

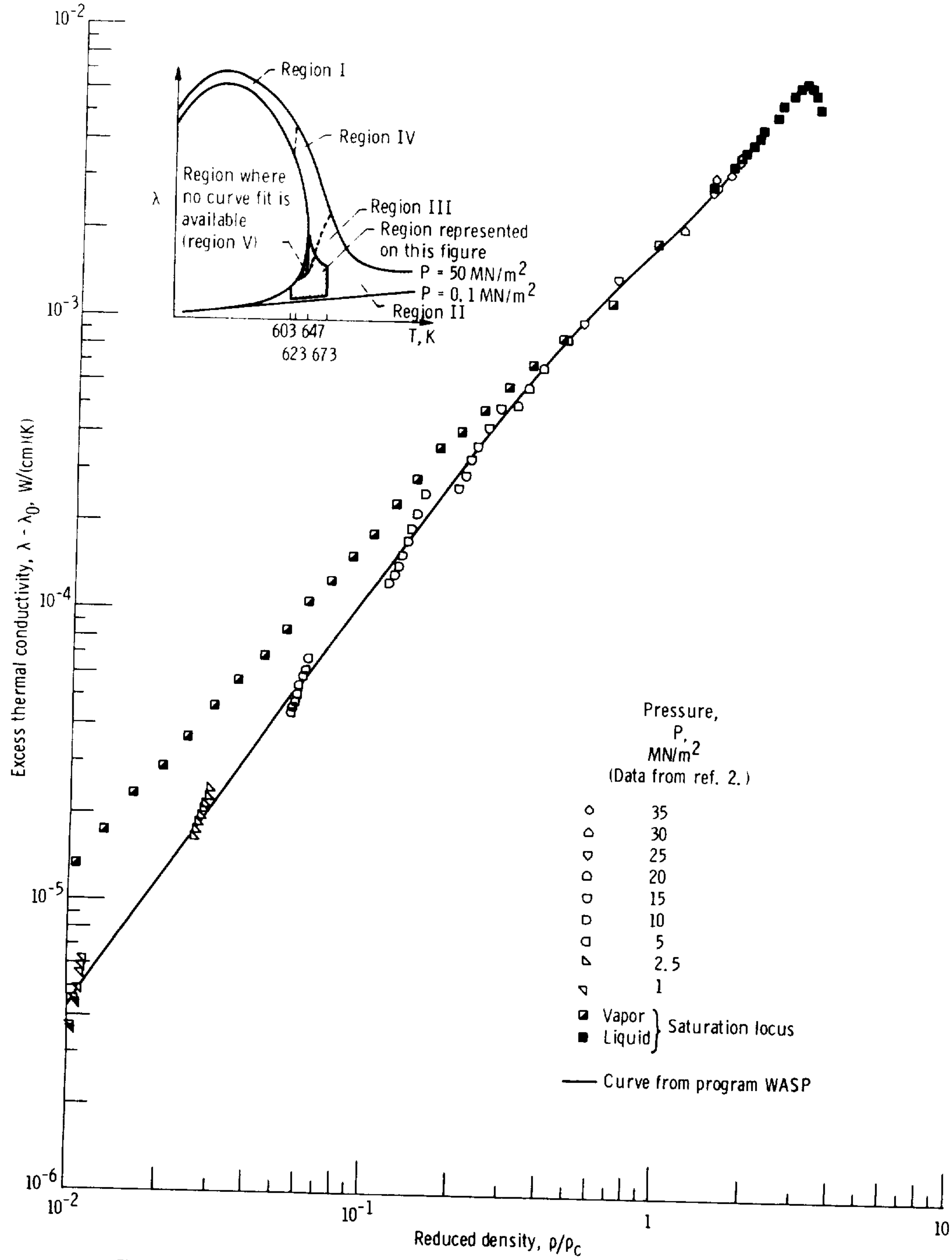


Figure 2. - Excess thermal conductivity as function of reduced density for region 603 K ≤ T ≤ 673 K.

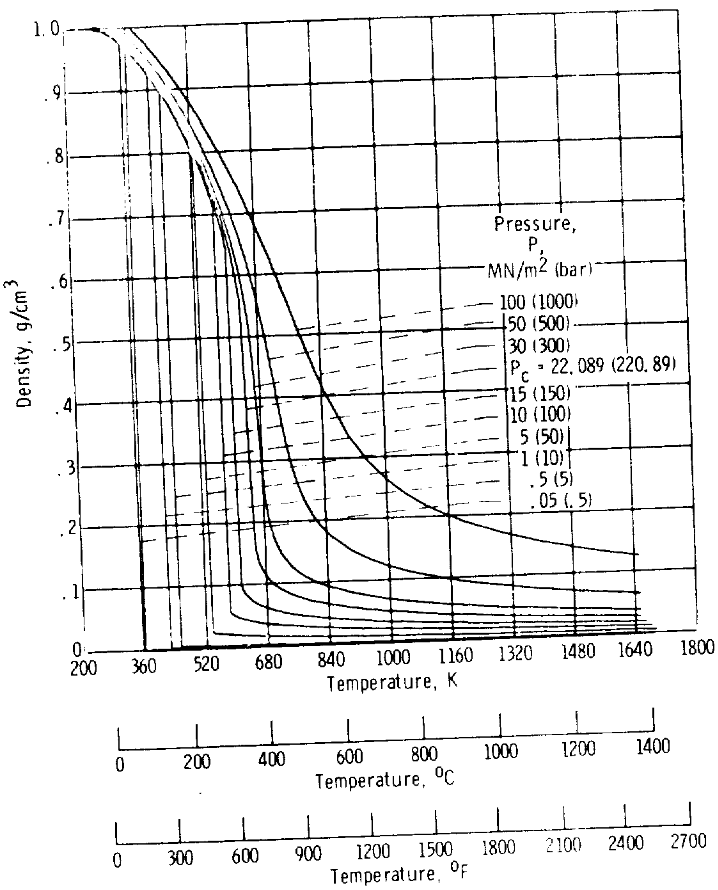
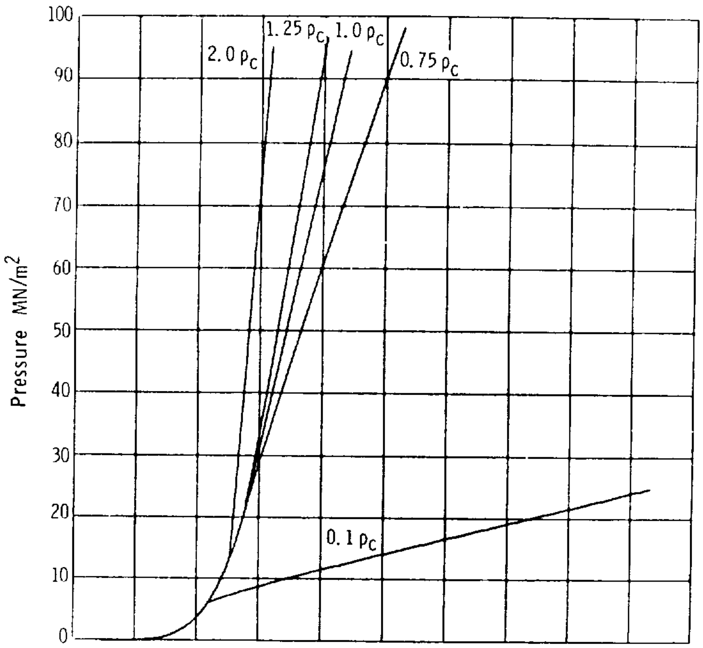
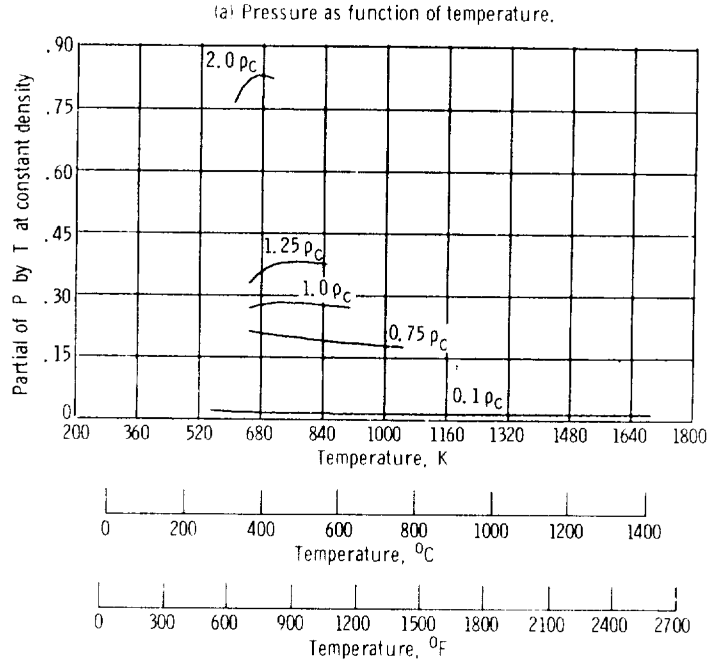


Figure 3. - Density as a function of temperature for selected isobars.



(a) Pressure as function of temperature.



(b) $\partial P/\partial T)_\rho$ as function of temperature.

Figure 4. - Pressure and the derivative $\partial P/\partial T)_\rho$ as function of temperature for selected isochores.

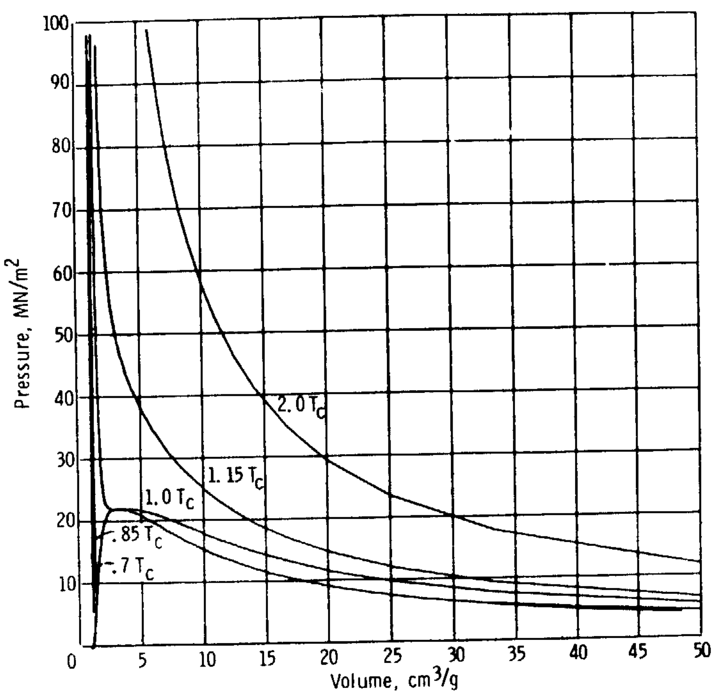


Figure 5. - Pressure as function of specific volume for selected isotherms.

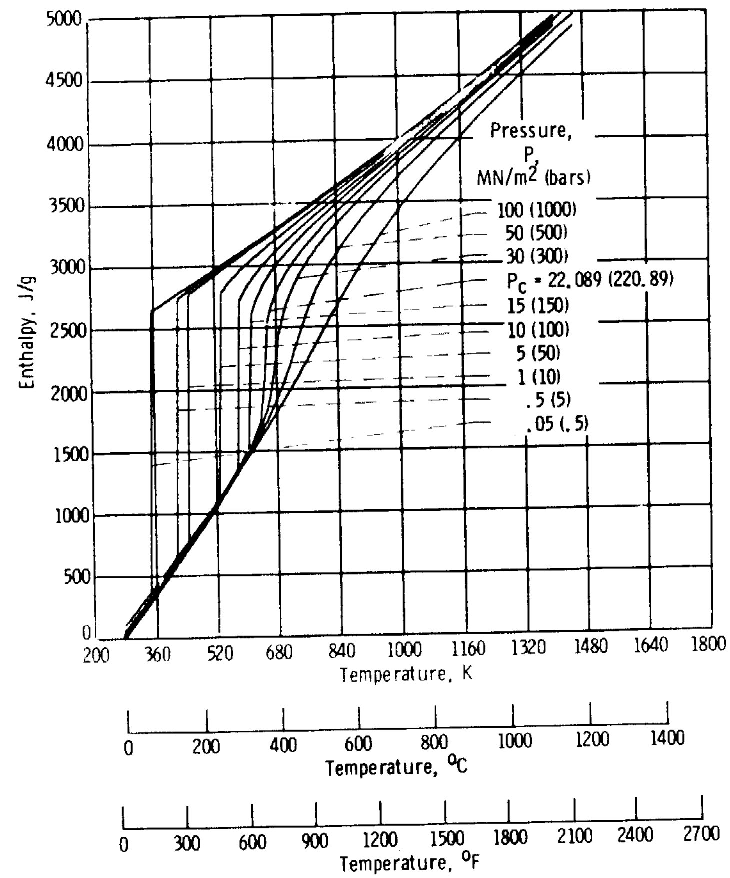


Figure 6. - Enthalpy as function of temperature for selected isobars.

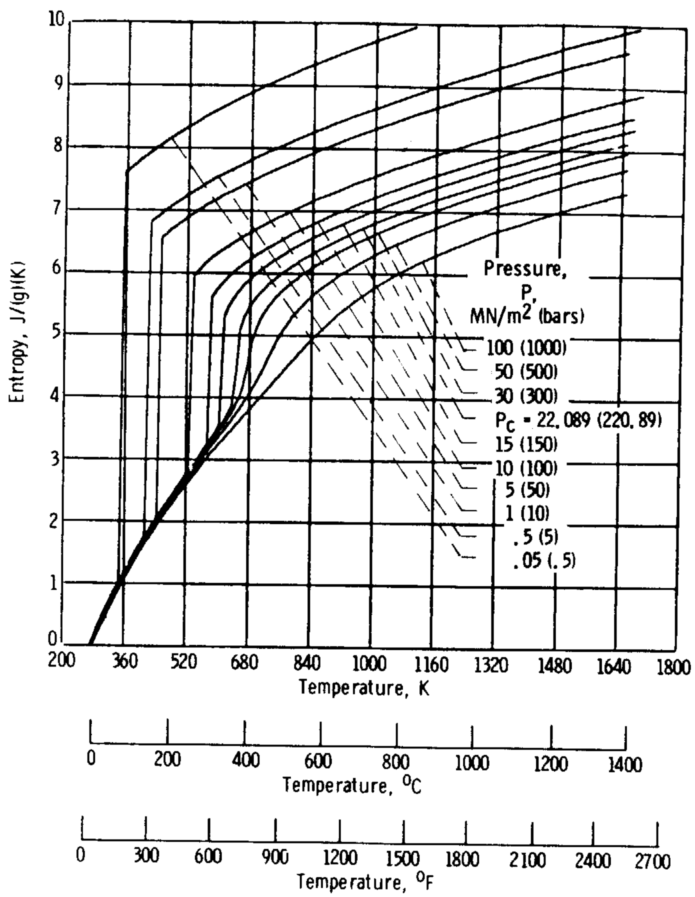


Figure 7. - Entropy as function of temperature for selected isobars.

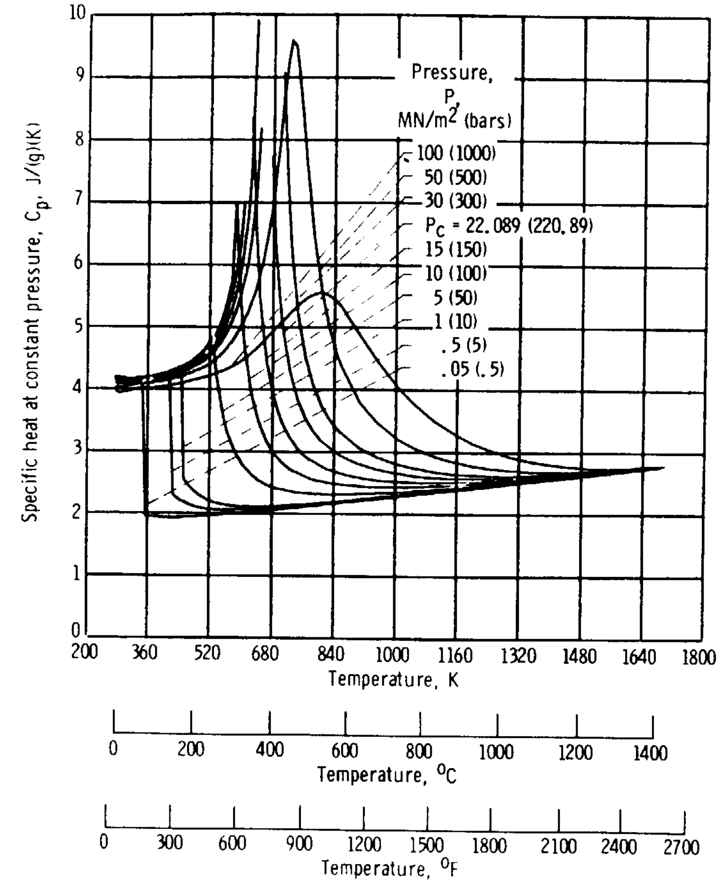


Figure 8. - Specific heat at constant pressure as function of temperature for selected isobars.

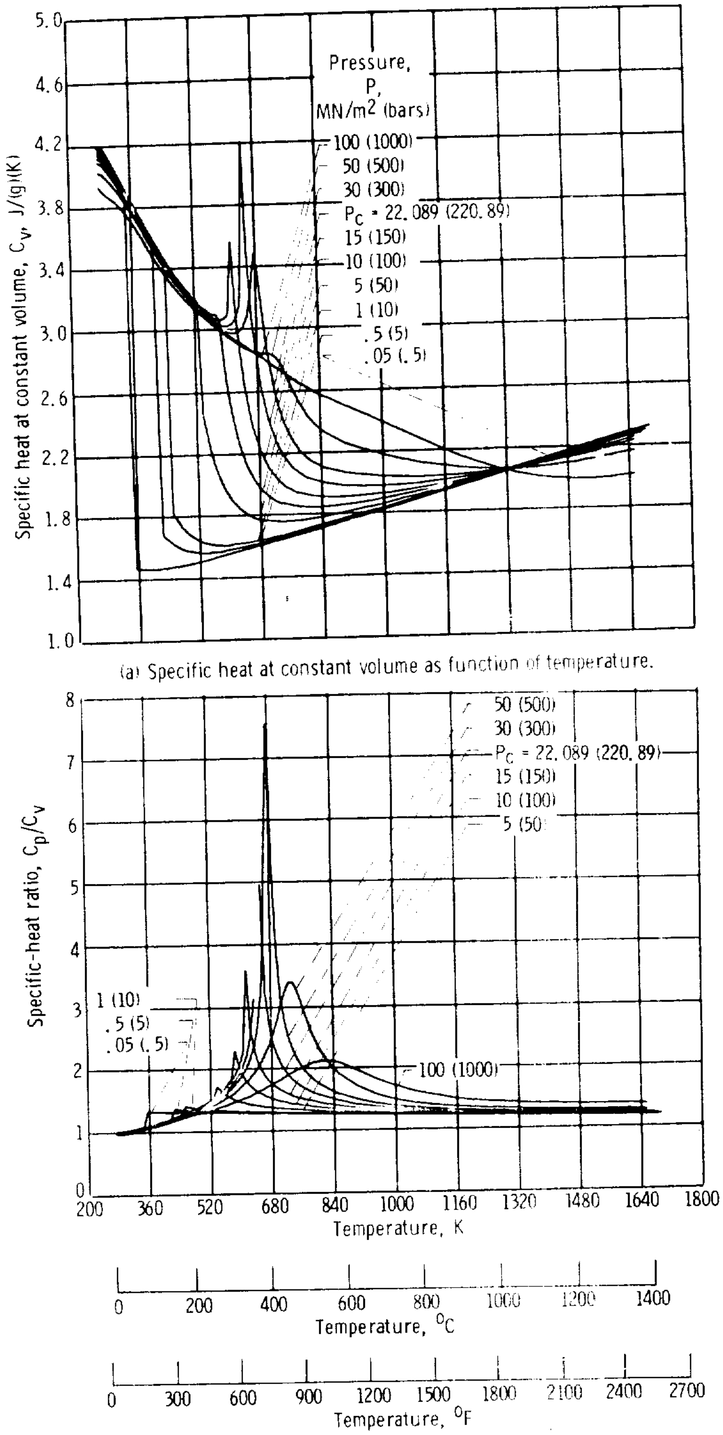


Figure 9. - Specific heat at constant volume and specific-heat ratio C_p/C_v as function of temperature for selected isobars.

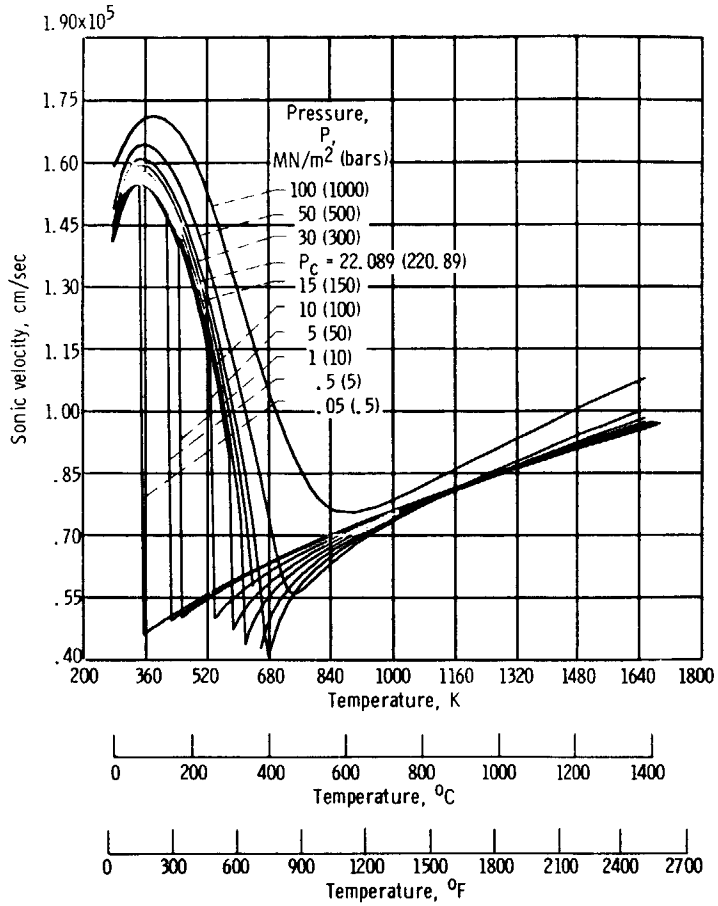


Figure 10. - Sonic velocity as function of temperature for selected isobars.

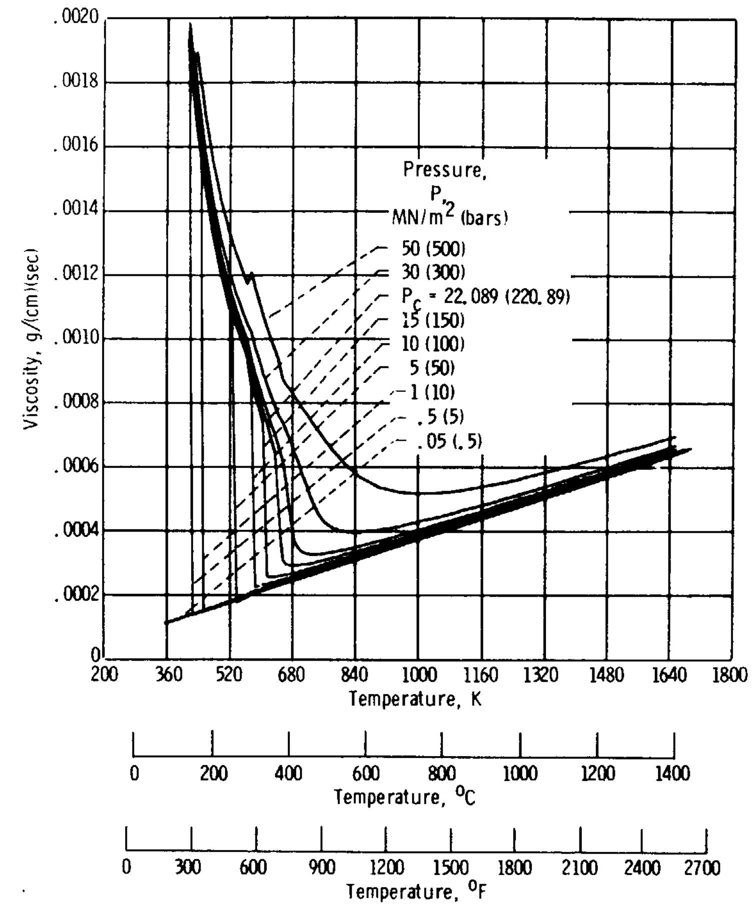
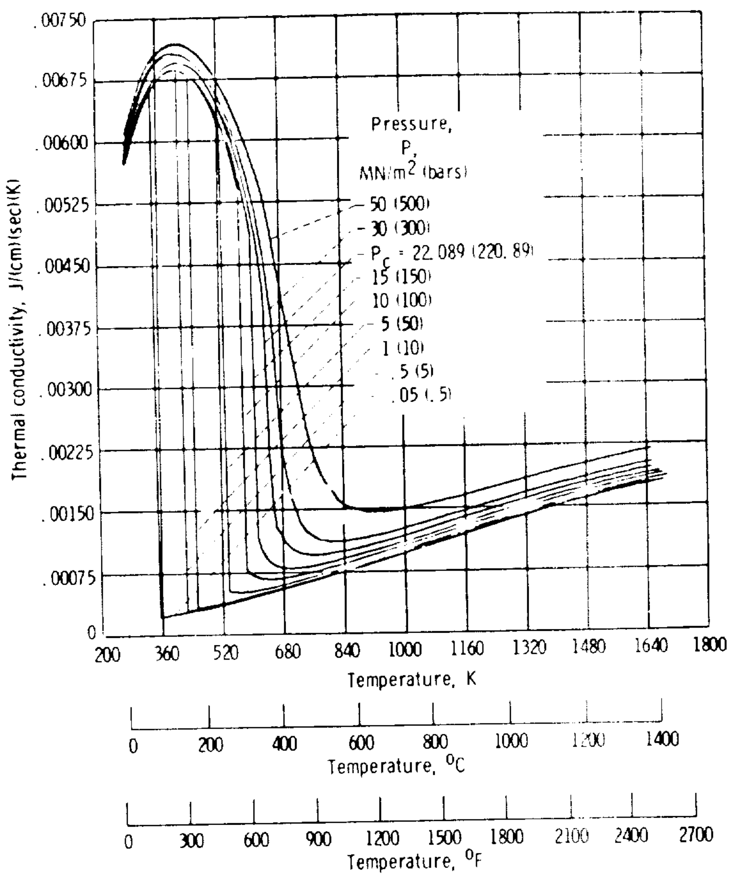
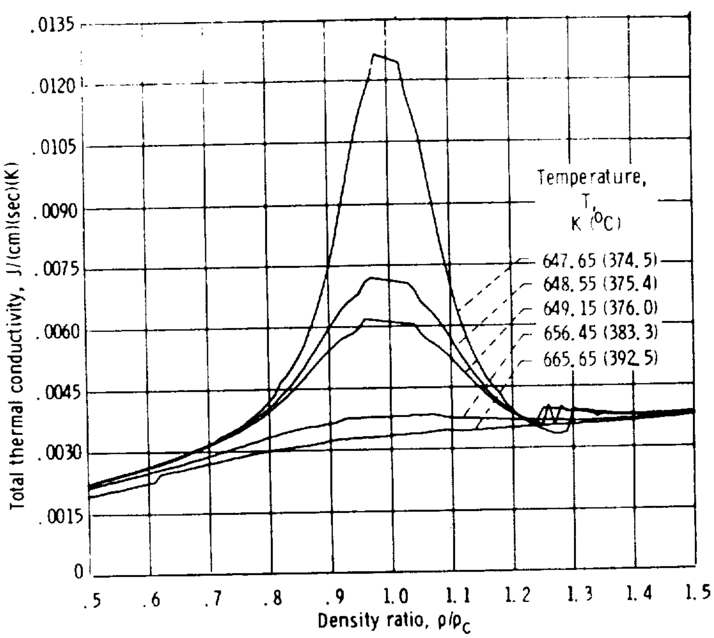


Figure 11. - Viscosity as function of temperature for selected isobars.



(a) Thermal conductivity as function of temperature for selected isobars.



(b) Approximation to anomalous behavior of thermal conductivity for water in the near-critical thermodynamic state.

Figure 12. - Thermal conductivity as function of temperature for selected isobars and total thermal conductivity as function of density ratio for selected isotherms.

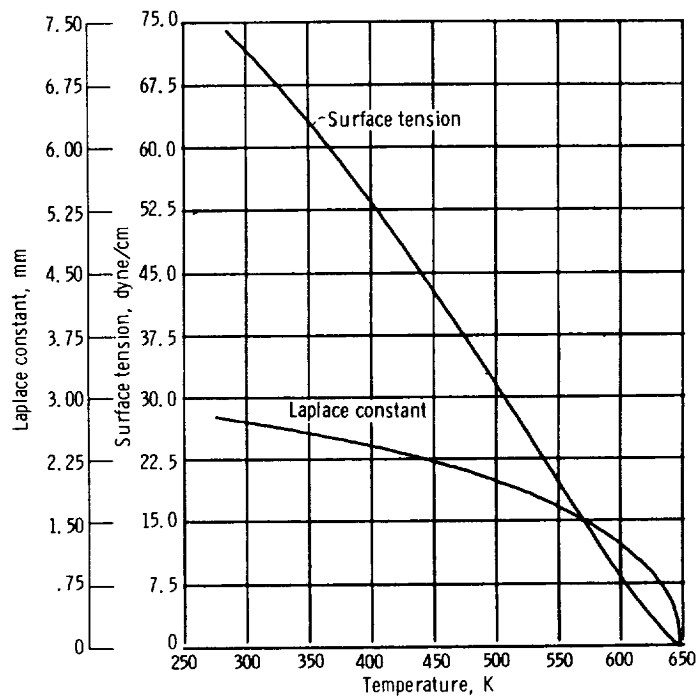


Figure 13. - Surface tension and Laplace constant as function of temperature.

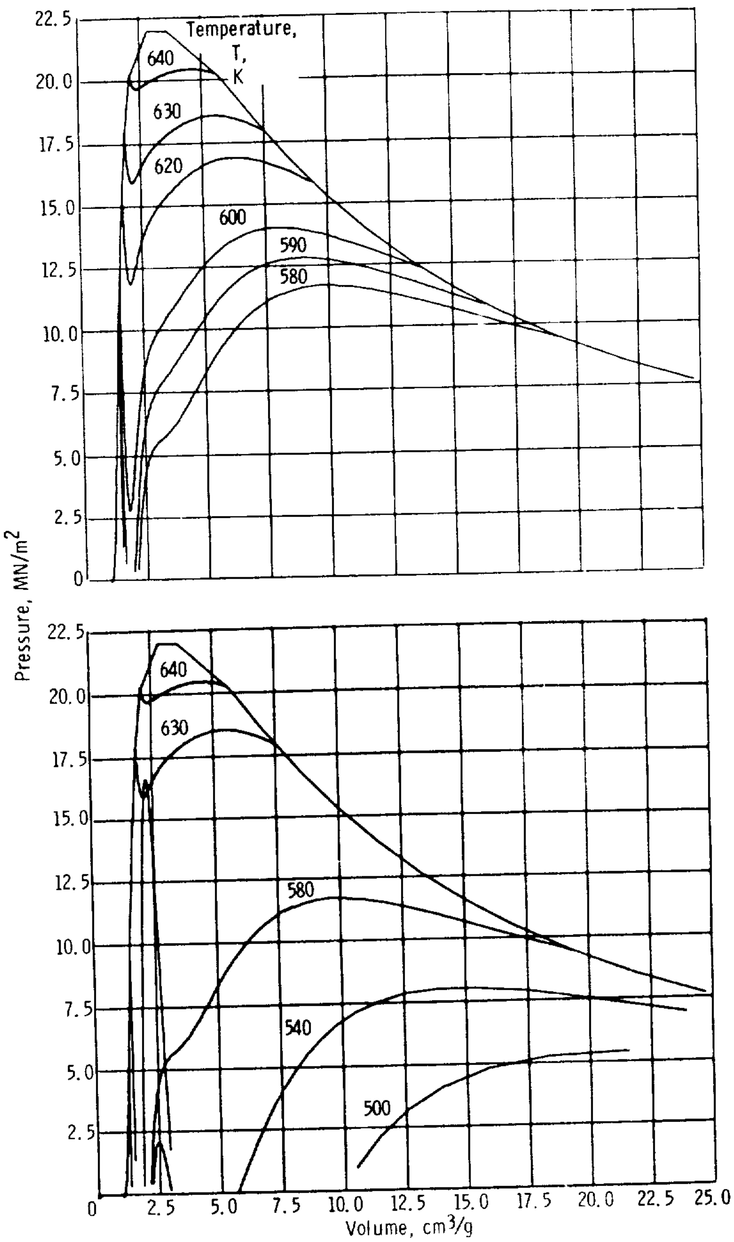


Figure 14. - Pressure-volume relations for metastable region along selected isotherms.

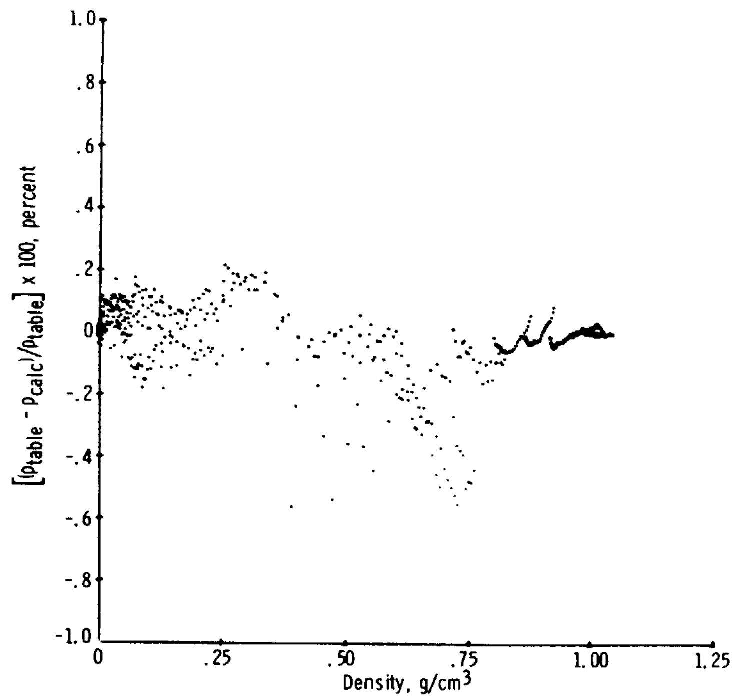


Figure 15. - Density differences as function of density. Comparison of WASP calculated PVT to International Skeleton Tables.

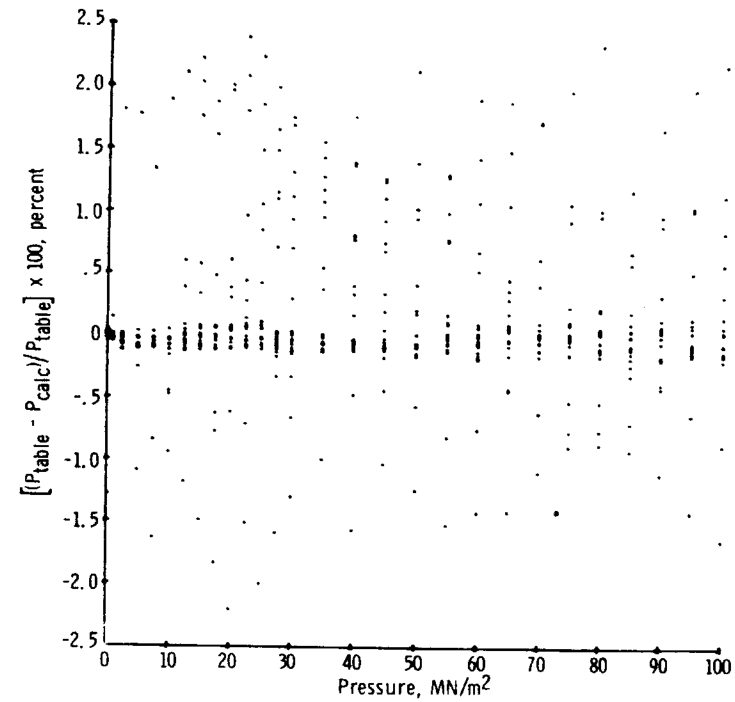


Figure 16. - Pressure differences as function of pressure. Comparison of WASP calculated PVT to International Skeleton Tables.

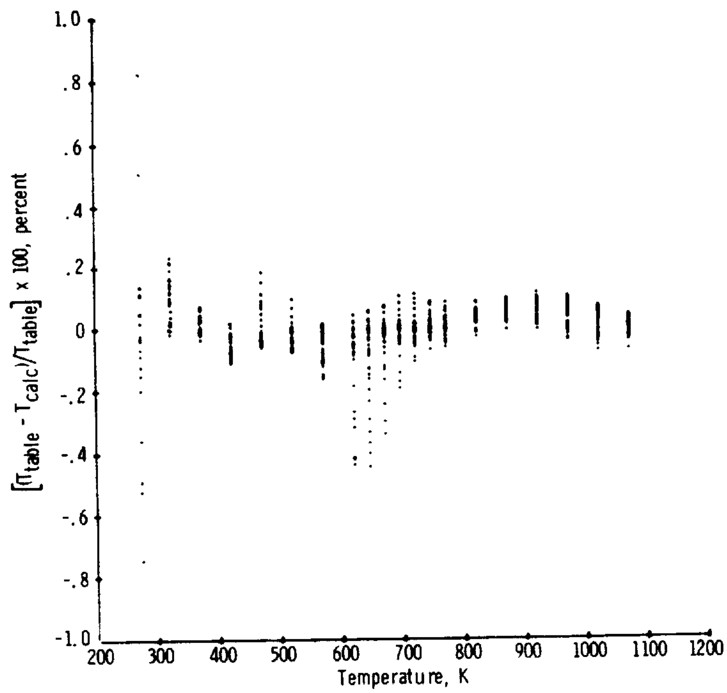


Figure 17. - Temperature differences as function of temperature. Comparison of WASP calculated PVT to International Skeleton Tables.

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